Evaluating Membrane Processes for Drinking Water Treatment Design

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Summary

The objective of this case study is to help undergraduate students apply engineering theory to the principles and scope of designing membrane systems for drinking water treatment. The case study outlines the activities of an engineering consulting firm that has been contracted to submit a preliminary design for a new water treatment plant for a rural community in Nova Scotia, Canada. The design is required to replace existing 20-year old facility and concur with new treatment standards for municipal surface source water treatment facilities established by the regulator. Preliminary analysis of water samples shows a source water that has low alkalinity, elevated color from naturally occurring matter (NOM) and seasonal spikes of turbidity and manganese. Additional challenges associated with this project include adapting the final design into the current infrastructure in terms of operational, maintenance and footprint constraints. This case presents the treatment capabilities of the existing treatment train as compared to a proposed design based on membrane filtration. Specifically, a review of the results of pilot-scale membrane trials leads the reader to critically examine the viability of membrane technology for small-scale water treatment applications within the context of meeting new drinking water standards.

Keywords: Water treatment plant design, membrane filtration, natural organic matter (NOM)

Context and Logistics

Learning Objectives

Through this case study, students will:

- gain an understanding of the basic principles of membrane processes for drinking water treatment; and

- learn to analyze water quality data with respect to potential impact to treatment performance.

Accommodating Course(s) and Level

- junior or senior level courses in water and wastewater treatment
- graduate level courses in water treatment plant design

Prerequisite Course(s)

- Water Quality/Environmental Chemistry
- Fluid Mechanics
- Introduction to Environmental Engineering

Type of Activity

- The case study can be discussed by the instructor as an in-class example, however may be best suited for in-class group exercise or administered as a group or individual student assignment.

Level of Effort by Instructor

- Review of the case study as an in-class example would use maximum one 60-minute lecture period. If administered as a group or individual assignment, grading time would be minimized by attached solutions.

Level of Effort by Individual Student

- Review of the case study would require maximum 60-minute, with solutions to questions accompanying the case another one hour.

Suggested Assessment Methods

- Question set which accompanies the case study will provide suitable assessment of student's understanding of the proposed engineering problems.

Introduction

Canadian Drinking Water Regulations

In Canada, drinking water quality objectives are based on the *Guidelines for Canadian Drinking Water Quality* (GCDWQ) as developed by the *Federal-Provincial-Territorial Subcommittee on Drinking Water*. The guidelines can be used by provinces to establish provincial drinking water regulations. The Province of Nova Scotia has adopted the GCDWQ as regulations for public drinking water supplies. In January, 2002 the Nova Scotia Department of Environment and Labour released a drinking water strategy which established new treatment standards for municipal surface source water treatment facilities. The major objective of these standards was to ensure public health through the development of potable water treatment systems which produce drinking water that is free of microbial pathogens. Multi-barrier treatment strategies that incorporate both physical removal (ie., coagulation/flocculation, sedimentation and filtration) and chemical inactivation (ie., disinfection) have been recognized as being critical to ensuring that systems in Nova Scotia meet current environmental standards. In particular, process selection should take into consideration the ability to satisfy all Maximum Acceptable Concentrations (MACs), Interim Maximum Acceptable Concentrations (IMACs) and Aesthetic Objectives (AOs) recommended in the *Guidelines for Canadian Drinking Water Quality* (GCDWQ).

Membrane Technology for Drinking Water Treatment

The advancement of membrane technology over the past ten years has resulted in an economically viable drinking water treatment solution for both large- and small-scale applications. From a fundamental perspective, membrane technology is based on the principle that these systems act as a physical, size-exclusion barrier to contaminants present in raw water feedstreams. Low-pressure membranes, microfiltration (MF) and ultrafiltration (UF), effectively remove suspended or colloidal particles via a sieving mechanism based on the size of the membrane pores relative to that of the particulate matter (USEPA, 2003). Dissolved substances that are smaller in dimension than the pores in a MF or UF membrane surface will pass through the surface of these membranes. As presented in Figure 1, UF membrane filtration with a rated pore size of 0.01 to 0.1 μm can effectively remove particulate matter and microorganisms via a size exclusion mechanism. However, based on the principle of pore size exclusion, dissolved material present in the feed water or wastewater streams (i.e., viruses, DOC and soluble inorganics) may not be effectively removed.

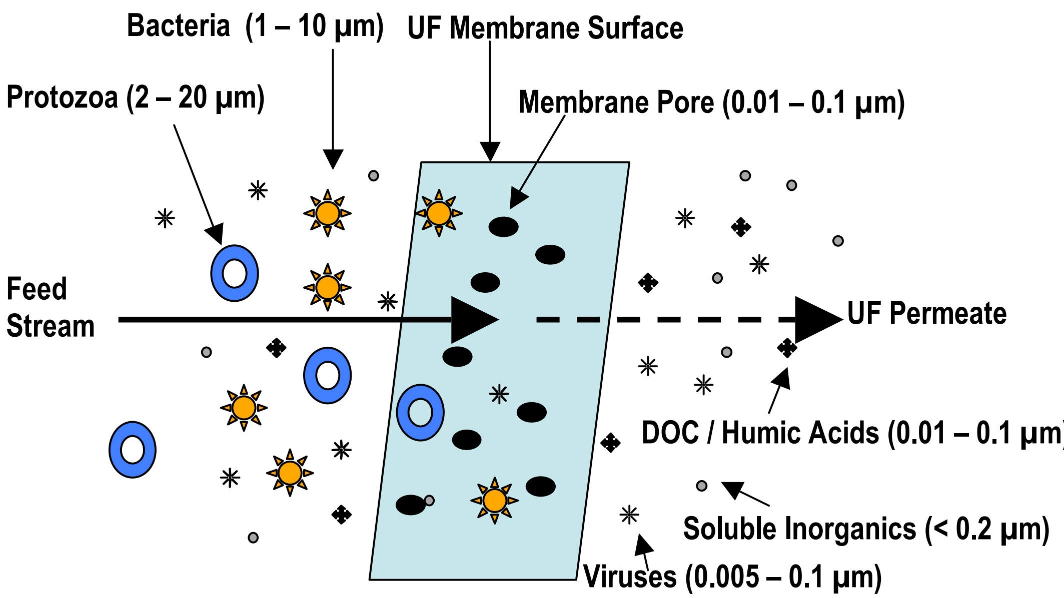

Figure 1. Conceptual drawing of UF membrane pore sieving mechanism (Walsh, 2005).

Design Parameters

1. *Flow configuration.* As presented in Figure 2, membrane systems can be operated in various process configurations. In a cross-flow configuration, a percentage of the concentrate (water that does not permeate through the surface of the membrane) is recirculated and blended with the feedwater. In a direct filtration configuration (dead-end filtration) there is no recirculation of the concentrate and system operation is based on 100 % recovery of the feedwater.

2. *Transmembrane pressure (TMP)* is the pressure that is used to drive water through the membrane. Positive pressure systems involve the pressurization of the feedwater that is then fed to the membranes. For immersed systems, the membrane modules are submerged in tanks containing the feed water and a negative pressure (i.e., vacuum) is applied to pull the treated water (permeate) through the fiber lumens. TMP can be calculated according to Tutujian (1985):

$$P_{tm} = \frac{(P_i + P_o)}{2} - P_p \qquad (1)$$

where P_{tm} = transmembrane pressure, [psi], P_i = pressure at the inlet of the membrane module, [psi], P_o = pressure at the outlet of the membrane module, [psi], and P_p = permeate pressure, [psi].

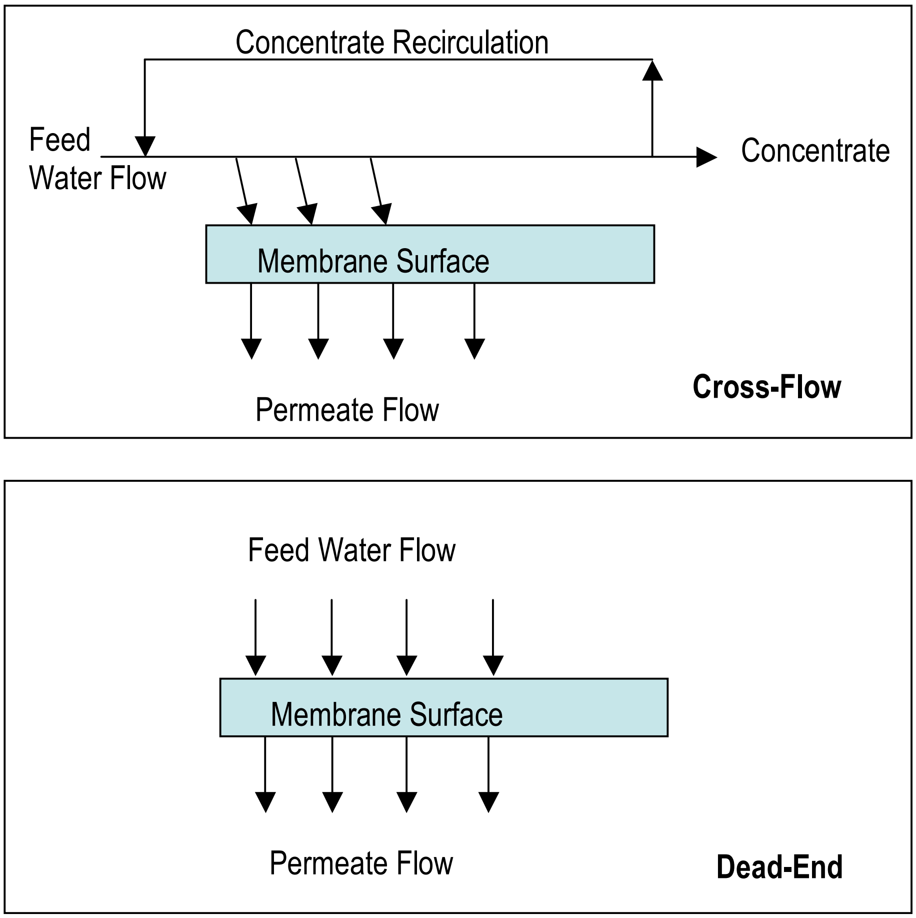

Figure 2 Membrane flow configurations.

3. *Permeate flux*, or ratio of permeate (membrane filtrate) flow rate to membrane surface area expressed as (L/ m²/ hr or gal/ ft²/ hr), is a major design factor used to determine the number of membrane units required for a specific plant capacity. To correct for temperature effects on water viscosity in flux calculations, Jacangelo *et al.*, (1994) proposed the following correction equation:

$$J_{20} = \frac{Q_p\, e^{-0.0239\,(T-20)}}{S} \qquad (2)$$

where J_{20} = permeate flux corrected for 20°C, [L/ m²hr], Q_p = permeate flow [L/ hr], T = permeate test temperature [°C], and S = membrane surface area [m²].

Often, design engineers will try to reduce overall capital cost of the membrane system through implementation of higher membrane fluxes. However, operating at higher design fluxes will inevitably increase operating costs due to higher operating pressures, more frequent cleaning and potential membrane replacement costs.

Specific flux (e.g., permeability) is defined as the ratio of permeate flux to TMP according to the following equation:

$$J_{sp} = \frac{J_{20}}{P_{tm}} \quad (3)$$

where J_{sp} = specific flux [L/ m²hr kPa], and P_{tm} = transmembrane pressure (TMP) [kPa].

4. *Recovery* is defined as the ratio of permeate flow to feedwater flowrate according to the following equation:

$$\% R = \frac{Q_P}{Q_F} \quad (4)$$

Low-pressure membranes (MF and UF) typically operate within the range of 85 – 97 % recovery. The rate of fouling and TMP will tend to increase when systems are operated at higher recovery rates.

Case Study

Background

An engineering consulting firm was contracted to evaluate the integration of low-pressure membranes into the current drinking water treatment facilities for a small community (i.e., < 1,000 residents) in rural Nova Scotia, Canada. The raw water source for the plant is the French River which flows through surrounding agricultural and natural land-use areas. The raw water quality is influenced by seasonal spikes in the Spring and Fall due to periods of high precipitation. A preliminary analysis of the raw water quality is presented in Table 1.

Table 1. Raw water quality analysis.

Analyte	Average Value	Seasonal Peak
Alkalinity, mg/L as $CaCO_3$	<10	17
Turbidity, NTU	2.0 – 4.0	4.5
TOC, mg/L	4.0 – 6.0	17.2
Color, TCU	40 – 50	197
Conductivity, µS	0.5 – 50	68

The existing water treatment plant for the community has a capacity of approximately 75,000 gal/day (0.3 ML/day) and consists of direct filtration (anthracite-sand) without coagulation or pre-oxidation unit operations. Liquid chlorine (NaOCl) is added to the filtered water to maintain a 0.2 mg/ L free chlorine residual in the distribution system. The key treatment concerns with the current plant treatment train are:

- Achieving a filtered turbidity less than 0.2 NTU
- Maintaining a free chlorine residual of 0.2 mg/ L during spikes in turbidity/organic matter
- Achieving a 0.5-log inactivation of *Giardia lamblia*
- Minimizing the potential to form disinfectant by-products (DPBs)

Pilot Studies

A membrane pilot study was conduced by the engineering consulting firm to investigate the treatment capabilities of low-pressure membrane systems (MF and UF) without chemical pre-treatment (i.e., coagulants) for this source water. This particular membrane application was somewhat unique in that the raw water quality is generally very good for the majority of the year. However, it requires robust treatment to respond to source quality variations during seasonal run-off periods. Specifications for the two membrane systems evaluated in the pilot studies are presented in Table 2.

Water Quality Results

The initial phase of the pilot trials involved operating the membrane modules without chemical pre-treatment. Samples were routinely taken from the raw water and permeate sample locations and analyzed for the water quality parameters outlined in Table 3.

Table 2. Characteristics of membranes used in pilot study.

Characteristic	MF	UF
Nominal Pore Size, µm	0.2	0.04
Filtration Area, m^2	0.80	0.93
Material	PVDF	PVDF
Filtration Configuration	Cross-flow	Dead-end
Operation Mode	Hollow fiber (inside-out)	Hollow-fiber (outside-in)
Operating Pressure, psi	3.0	-0.3 to -2.0
Operating Flux, L/ m^2hr	26.0	29.0
Backwash Mode	None	Permeate back-pulse

PVDF: polyvinylidene fluoride

Table 3. Average water quality results during phase 1 pilot trials.

Analyte	Raw Water	MF Permeate	UF Permeate
Turbidity, NTU	2.11	0.14	0.09
TOC, mg/L	8.22	4.51	2.34
Color, TCU	44.0	14.0	13.7
UV254, cm^{-1}	0.189	0.114	0.053

Both the MF and UF pilot systems achieved excellent removal of turbidity and significant reductions in color. However, the permeate water quality in terms of TOC and UV254 showed that the formation of DBPs after chlorination in the clearwell may pose regulatory problems for the water utility. Therefore, the second phase of the pilot trials involved the addition of aluminum sulphate ($Al_2(SO_4)_3 \cdot 14H_20$), or alum as a chemical pre-treatment to evaluate the impact on permeate water quality. Due to the low alkalinity of the raw water and results of jar tests conducted in the lab, the alum dosage selected for the membrane pilot trials was 15 mg/L. The results of this phase of the pilot study are presented in Table 4.

Flux and Permeability

During the 17-day Phase 1 pilot trials, operating data including system temperature, permeate flowrate and transmembrane pressure (TMP) was collected daily (Table 5). The MF module was operated under constant pressure with variable flux, while the UF module was operated under constant flux with variable TMP to compensate for membrane fouling.

Table 4. Average water quality results during phase 2 pilot trials.

Analyte	Raw Water	MF Permeate	UF Permeate
Turbidity, NTU	2.41	0.11	0.07
TOC, mg/L	7.98	0.86	0.43
Color, TCU	44.0	7.7	3.3
UV254, cm^{-1}	0.178	0. 501	0.012

Table 5. Membrane operating data during phase 1 trials.

Operating Time, days	System Temperature, °C	Permeate Flowrate, mL/min		TMP, psi	
		MF	UF	MF	UF
1	15.1	500	500	20	30
2	14.8	499	500	20	33
3	15.2	487	500	20	42
4	15.1	467	500	20	56
5	14.9	466	500	20	59
6	14.9	425	500	20	62
7	15.0	450	500	20	81
8	15.1	423	500	20	88
9	15.2	412	500	20	36
10	15.0	408	500	20	48
11	14.9	401	500	20	53
12	15.0	422	500	20	59
13	15.0	401	500	20	64
14	14.9	398	500	20	77
15	14.8	377	500	20	92
16	15.2	356	500	20	32
17	15.0	310	500	20	55

The loss of permeability in the UF and MF operating systems were calculated to be 32 % and 44 %, respectively, during the Phase 1 trials without the addition of a coagulant. However, permeability losses were reduced to 28 % and 26 % for the MF and UF systems during the Phase 2 trials with alum addition.

Based on the water quality and operating results of the pilot study, the consulting firm decided that a two-stage UF treatment system with alum coagulation pre-treatment (15 mg/ L) would offer the most efficient and economical treatment solution for the given raw water quality and operating constraints of the plant (Figure 3). With this design, the first-stage UF system backwash water is recovered and treated by a second UF membrane system in order to optimize recovery rates and reduce system cleaning requirements while still maintaining desired finished water quality. Specifically, the design would allow for a lower feedwater recovery in the first stage (85 %) resulting in reduced membrane surface area required for this stage while achieving overall feedwater recovery of 99 %.

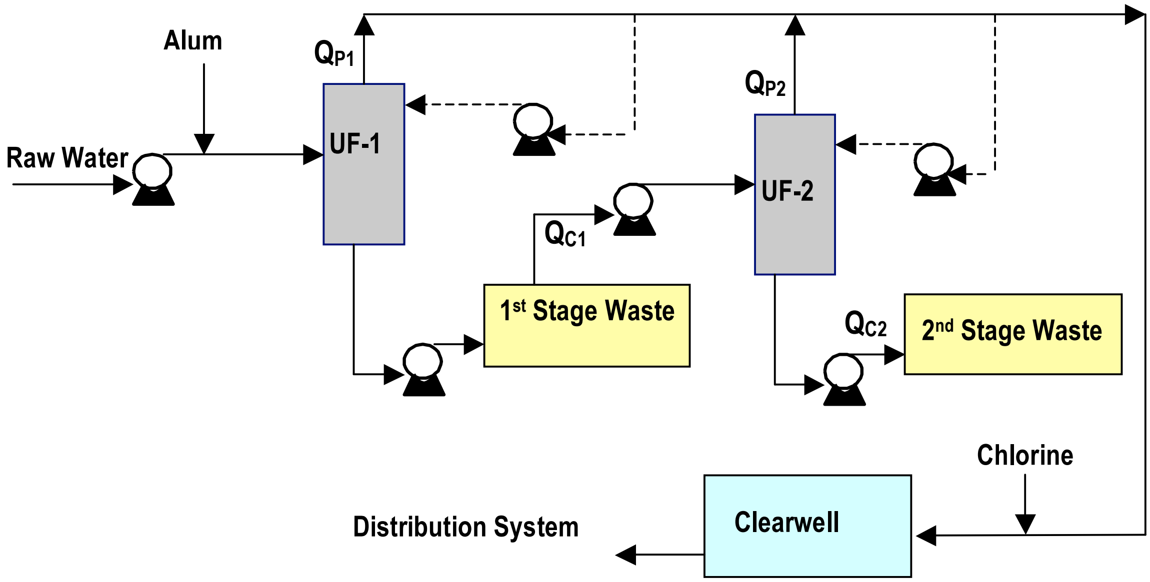

Figure 3. Process schematic of the proposed two-stage UF plant.

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Questions

1. Based on the fundamental separation mechanism of pore size exclusion, explain the water quality results observed during the Phase 1 pilot trials. Based on these results, what would be the main driving factor for the consulting firm initiating a second phase of pilot trials to include chemical pre-treatment with alum? What other coagulants could potentially be used in this design?

2. What further testing should the consulting firm have included during the pilot study to evaluate *Giardia lamblia* removal rates?

3. The final design for the membrane plant was based on a dead-end flow configuration with UF membrane modules. What advantages in terms of capital cost would this design afford the water utility? What would be the main operational cost savings that could be achieved with a cross-flow configuration?

4. The alum dosage selected for Phase 2 of the pilot study was 15 mg/L based partly on the low alkalinity of the raw water. How much alkalinity (as $CaCO_3$) would be consumed by this alum dose? What modification to the pre-treatment design would have to be made if the results of the jar tests showed that an alum dose of 50 mg/L would be required? Would an alum dose of 50 mg/L be a reasonable or realistic dosage for this design?

5. Using the pilot study operating data presented in Table 5, calculate and graph the daily permeate flux and permeability of the MF and UF membranes during the Phase 1 pilot trials. Explain possible reasons for the periodic spikes in permeability of the UF membrane during the 17-day trial.

6. Based on the two-stage UF design (Figure 3) proposed by the engineering consulting firm and knowing that the first membrane can just achieve the design permeate goals for TOC and turbidity, what is the permeate TOC concentration leaving the second membrane?

Analysis

- Phase 1 water quality results showed high removal rates of turbidity (MF=93 %, UF= 96%). Based on the mechanism of pore size exclusion, these results would indicate that a significant fraction of matter contributing to turbidity was in the particulate fraction (i.e., particle size > 0.04 µm). Lower removal rates for organic matter as measured by TOC

(MF= 45 %, UF= 72%) indicate that dissolved organic carbon (DOC) may represent a considerable fraction of the TOC present in the raw water. These results are supported by color and UV-254 measurements, for which reduced removal rates were achieved with MF and UF membrane filtration indicating that the concentration of dissolved organic material in the raw water would warrant pre-treatment (i.e., coagulation) to enhance overall removal efficiencies. Polyaluminum chloride (PACl), ferric salts such as ferric sulphate ($Fe(SO_4)_3$) or ferric chloride ($FeCl_3$), or synthetic coagulating agents such as polyacrylamides would also be viable coagulants that could be evaluated with this water.

- Particle count analysis would provide additional data on permeate water quality in terms of removal of particles within size range of *Giardia lamblia* (2 – 15 μm) and other pathogens (i.e., Cryptosporidium, 2 – 5 μm). As a surrogate monitoring technique, particle counting determines particle sizes and thus warns of particles in the size range of oocysts and cysts.

- Dead-End Flow Configuration: Recirculation pumps and associated piping not required resulting in reduced capital costs and operational cost savings due to reduced energy input.

- $Al_2(SO_4)_3 \cdot 14.2H_20 + 3Ca(HCO_3)_2 \rightarrow 2Al(OH)_3\ (s) + 3CaSO_4 + 6CO_2 + 18H_20$

  Molecular Weight of $Al_2(SO_4)_3 \cdot 14.2H_20$ = 597.9 g/mol
  Molecular Weight of $Ca(HCO_3)_2$ = 162. 1 g/mol
  Molecular Weight of $CaCO_3$ = 100.1 g/mol

  Alkalinity Consumed =
  (15 mg/L) x (mol/597.9 g) x (g/1000mg) x (3mol $Ca(HCO_3)_2$/mol alum) x (2eq $Ca(HCO_3)_2$/mol) x (1eq $CaCO_3$/1eq $Ca(HCO_3)_2$) x (mol $CaCO_3$/2eq $CaCO_3$) x (100.1g $CaCO_3$/mol $CaCO_3$) x (1000 mg/g)

  Alkalinity Consumed = 7.5 mg/ L

  Due to low alkalinity of raw water source (e.g.., < 10 mg/L as $CaCO_3$), higher dosages of alum would require addition lime ($Ca(OH)_2$) or caustic (NaOH) prior to alum addition. However, the need for higher alum dosages (i.e., > 30 mg/ L) would not be expected for membrane pre-treatment design, due to the anticipated size of floc formation relative to membrane pore size.

- Calculations/graphs in attached excel file.

The results of this pilot study showed the UF system had a lower permeability as compared to the MF operating system although the former system operated at an elevated TMP. However, the smaller nominal pore size of the UF pilot system (0.04 μm) compared to the MF pilot system (0.2 μm) would influence the permeability of the membranes evaluated. Throughout the 17-day pilot trial, the TMP of the UF system gradually increased and permeability decreased as the permeate flowrate was held constant indicating that fouling of the membrane surface over time was occurring. On days 8, 15 and 16 the TMP decreased to pressures seen at the beginning of the trial (i.e., 30 -35 psi) indicating that foulant material had been removed from the membrane surface through chemical cleaning procedures. Similar trends are visible on the MF permability profile although under constant pressure, these spikes are not visible in the permeate flux graph.

- See attached Excel File.