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The pros and cons of using nanofiltration in lieu of reverse osmosis for indirect potable reuse applications

Christopher Bellona [a,b], Dean Heil [a], Christopher Yu [c], Paul Fu [d], Jörg E. Drewes [a,*]

[a] Advanced Water Technology Center (AQWATEC), Department of Civil and Environmental Engineering, Colorado School of Mines, Golden, CO 80401, USA
[b] Department of Civil and Environmental Engineering, Clarkson University, Potsdam, NY 13699, USA
[c] PSOMAS, Santa Ana, CA 92707, USA
[d] Water Replenishment District of Southern California, Lakewood, CA 90712, USA

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ABSTRACT

In recent years, considerable interest has been given to using nanofiltration (NF) in lieu of reverse osmosis (RO) for water reclamation applications. This work first examined the operational and rejection performance of several NF membranes compared to a commonly employed RO (ESPA2) membrane at a water reclamation facility. Rejection performance of the NF membranes mainly differed for monovalent ions, however, operational performance characterized by specific flux and flux decline differed substantially among the membranes evaluated. Based on preliminary testing, a promising NF membrane (NF270) was selected for pilot-scale testing and compared to pilot- and full-scale operation of the ESPA2 membrane. While the ESPA2 membrane exhibited significant flux decline primarily due to second stage scale formation, the NF270 membrane exhibited minimal flux decline, presumably due to the partial passage of sparingly soluble salts. Additionally, the NF270 membrane operated at a specific flux double that of the ESPA2 membrane and exhibited minimal flux decline at elevated recovery (87–88%). The major limitation with the NF270 membrane is the poor rejection of nitrate and inability to meet the California TOC requirements of less than 0.5 mg L^{-1}. NF270 membrane permeate TOC concentrations were only marginally greater than the ESPA2 membrane and averaged 0.62 mg L^{-1} during 1300 h of testing. The rejection of a wide range of trace organic chemicals was evaluated during ESPA2 and NF270 membrane pilot-scale testing. Analysis of feed and permeate samples collected during NF270 membrane testing revealed that although more compounds could be detected in NF270 membrane permeate samples compared to the ESPA2 membrane, concentrations with the exception of atenolol and TCEP were consistently less than 100 ng L^{-1}, which is significantly below any toxicological threshold level. An economic analysis using information gained through pilot-scale testing and full-scale operation revealed that significant cost savings could be achieved by using a low-pressure NF, such as the NF270 membrane.

1. Introduction

High-pressure membrane processes, such as reverse osmosis (RO) and nanofiltration (NF) membranes, are becoming increasingly widespread in water treatment, industrial processes, and wastewater reclamation/reuse applications where a high product water recovery is desired [3]. For surface water augmentation and groundwater injection projects using reclaimed water in the United States, Europe, Singapore and Australia, treatment schemes using an integrated membrane system (IMS), such as microfiltration (MF) pretreatment, followed by RO is considered the industry standard [17]. Although this IMS approach for reclaiming wastewater especially for groundwater recharge is becoming more widespread, numerous challenges exist, including selecting appropriate membranes, fouling and scaling issues, energy requirements, and the removal of chemicals of emerging concern (e.g., trace organic chemicals). Currently, the California Department of Public Health (CDPH) Draft Groundwater Recharge Requirements specify that IMS plant effluent must not exceed 5 mg nitrogen per liter (mg-N/L) of total nitrogen (TN) and 0.5 mg L^{-1} of TOC for projects where no dilution in the subsurface is occurring [6].

Several recent research studies have evaluated alternate membranes, such as low-pressure reverse osmosis (LPRO) and NF membranes, for IMS applications to lower the energy requirements associated with RO [5,4]. Through laboratory testing, several promising LPRO and NF membranes were identified based on rejection performance and initial permeability, however, pilot-scale testing revealed significant flux decline due to effluent organic matter (EfOM) fouling. Besides the potential fouling and flux decline issues, previous research has demonstrated that although NF and low pressure reverse osmosis (LPRO) membranes can achieve a

* Corresponding author.
E-mail address: jdrewes@mines.edu (J.E. Drewes).

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high removal of total organic carbon (TOC), the rejection of inorganic monovalent ions such as ammonia and nitrate can be low, depending on the membrane [5,15,22]. Furthermore, incomplete rejection of various endocrine disrupters (synthetic and natural hormones), pharmaceutically active compounds (PhACs), disinfection by-products, (e.g., N-nitrosodimethylamine), and other organic compounds (e.g., 1,4-dioxane) by RO, LPRO, and NF membranes have been reported by previous studies [21,12,13,18,19].

A recent study by Yangali-Quintanilla et al. [25] reported that the use of NF (NF90, Dow/Filmtec) in lieu of RO (BW30LE, Dow/Filmtec) could result in cost savings ($53 k/year for a 100 m^3/h facility) due to reduced energy, chemical and concentrate disposal costs. Conclusions drawn from this study, however, were based on RO design software and results from previously conducted research using virgin membranes. A past study evaluating NF-90 membrane performance at pilot-scale reported that the initial high permeability of this membrane was significantly reduced due to EfOM fouling [4]. Additional pilot-scale testing indicated that significant cost savings associated with lower feed pressure is generally limited to several low fouling, 'loose' NF membranes. Furthermore, most of the previous studies investigating rejection performance and permeability of membranes for water reuse applications have been performed at bench-scale, using flat-sheet membrane units or dead-end filtration cells [7,2,11]. Many studies have also utilized deionized water spiked with target solutes, as well as virgin membrane specimens neglecting water matrix effects and membrane property changes because of the fouling commonly observed in full-scale membrane applications [14,1]. In order to properly evaluate the rejection and flux performance of NF and LPRO membranes representative of full-scale conditions, a more thorough long-term investigation at pilot-scale is required.

The objective of this study was to evaluate the performance of several NF membranes for water reuse applications and compare the performance to a commonly used RO membrane. Performance criteria included permeability (i.e., temperature corrected specific flux), flux decline, and the rejection of nutrients, salts, organic carbon and trace organic chemicals. Three NF membranes and one RO membrane were evaluated at a water reuse facility using a 2-spiral wound element testing unit. Pilot-scale testing using a 80-L/min 2-stage membrane skid was conducted with an RO membrane and a promising NF membrane for more than 1300 h each.

2. Material and methods

2.1. Membranes evaluated

Based on previous studies conducted by the authors, three promising NF and one LPRO membrane (Table 1) were targeted for this study, including the RO membrane ESPA2 (Hydranautics, Oceanside, CA) and the NF membranes NF-270 (Dow/Filmtec, Midland, MI) and TFC-S and TFC-SR3 (Koch Membrane Systems, Wilmington, MA)). These membranes were pre-selected because of their high flux rates at low pressure and their low fouling propensity exhibited during previous investigations [8]. The ESPA2 membrane served as the baseline membrane as it is currently employed at several water reclamation facilities practicing groundwater recharge including the facility where testing was performed for this study.

2.2. Testing systems

Two customized membrane testing systems were used during this study: a two-spiral wound element (4040) testing system and a 2-stage pilot-scale system designed to mimic the hydrodynamic conditions of a full-scale membrane treatment train. Prior to pilot-scale testing, candidate membrane screening was performed to identify the best membrane for pilot-scale evaluations. The water reuse facility where testing occurred treats disinfected tertiary effluent with MF, RO, and ultraviolet radiation, which is then blended with imported water from the Metropolitan Water District of Southern California (MWD) and subsequently injected into a seawater intrusion barrier. During membrane testing, MF filtered tertiary wastewater effluent was taken from a buffer tank and used as feed water to the membrane systems.

2.2.1. Two-element system

The operation and rejection performance of the candidate membrane was evaluated utilizing a test system with two-spiral wound elements (4040) in two pressure vessels in series. The unit had a supervisory control and data acquisition (SCADA) system that downloads operational data including system flow rates, pressure, conductivity, and temperature. Actual candidate membrane operation and rejection experiments were performed at the water reclamation facility by diverting MF filtrate to the laboratory-scale testing unit. Rejection experiments were conducted at permeate flux rates of approximately 25.5 LMH ($7.1 \times 10^{-6}\ m^3\ m^{-2}\ s^{-1}$) at a recovery of approximately 30%. Samples for water quality analysis were collected from the feed and permeate streams of the testing unit. For each membrane, samples were collected for water quality, and the membrane system was allowed to run over-night (~24 h) to evaluate the initial flux decline caused by fouling.

2.2.2. Pilot-scale system

The pilot-scale system used was a two-stage membrane unit with a capacity of 80 L/min. The unit was built in a four-stage array configuration to minimize space and consisted of six pressure vessels, four in the first stage and two in the second stage. The pilot-scale unit required 21, spiral-wound 4040 elements, with 14 elements in the first stage and 7 elements in the second stage. The system had a variable speed feed pump and was operated at different recoveries (varying between 85% and 88%), feed-flow rates, and permeate flux. While one recovery set-point was chosen, the system was operated by controlling the applied pressure as a variable to obtain a constant permeate flux. The pilot was equipped with a customized SCADA system to monitor and log flow rates, pressures, and selected water quality parameters online (e.g., pH, temperature, and conductance). Further details of the system are provided in Drewes et al. [8].

Table 1
Membranes evaluated and relevant performance information.

Candidate membrane	ESPA2	NF-270	TFC-S	TFC-SR3
Classification	RO/LPRO	NF	LPRO/NF	NF
Manufacturer	Hydranautics	Dow/Filmtec	Koch	Koch
Material	Polyamide	Polypiperazine	Polyamide	Polyamide
NaCl Rejection (%)	99.6[a]	NA	85[a]	30–50[a]
MgSO4 Rejection (%)	NA	>97[a]	99[a]	NA
MWCO (Daltons)[b]	<100	~200	~150	~200[a]

[a] From manufacturer.
[b] Computed during rejection experiments unless otherwise noted.