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An experimental system for characterization of membrane fouling of solar photovoltaic reverse osmosis systems under intermittent operation

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ABSTRACT

Many remote communities struggle to provide a reliable source of clean drinking water. Solar photovoltaic reverse osmosis (PVRO) systems are a stand-alone water purification technology that can help alleviate this need. A challenge associated with these systems is the variation in the available energy, and as a result, the systems are typically designed to operate intermittently which can cause premature membrane fouling. During the design of PVRO systems, basic approximations are typically used to evaluate the performance and economic impact of this membrane fouling caused by intermittent operation. However, this fouling has not been characterized experimentally. This paper describes an experimental lab-scale reverse osmosis system which was developed to study the effects on membrane fouling of this intermittency. The system consists of three stainless steel cross-flow reverse osmosis membrane cells connected in parallel, equipped with automated valves and pumps to evaluate different pre-treatment options, and instrumented to characterize the operating parameters and membrane fouling. This system was used to preliminarily characterize membrane fouling for intermittent operation common of PVRO systems. Two reverse osmosis operating modes were studied, continuous operation (24 h/d) and intermittent operation (8 h/d). During these experiments, it was shown for surrogate brackish water with minimal biological content, there was not a significant change in membrane fouling due to intermittent operation. This experimental system will be applied in future experiments to further evaluate membrane fouling under other operational conditions typical in PVRO systems and extracted models will be used in modular design methods for custom PVRO systems that are robust to variability in operating conditions.

Keywords: Desalination; Reverse osmosis; Brackish water; Photovoltaics; Modular design; Small-scale reverse osmosis water purification

1. Introduction

1.1 Motivation

Globally, over 760 million people lack access to improved drinking water and its associated health benefits [1]. They rely instead on seasonally available water sources (cisterns, boreholes, and wells) that often contain chemical contaminants and bacteria [1]. These communities also have limited access to electricity [2] and connecting to large-scale water treatment plants through the water supply infrastructure is not economically viable due to their remote locations. Diesel generators are a common power source for remote communities [3]. However, the high cost of fuel and environmental pollution has limited their use for water treatment [4]. Solar photovoltaic reverse osmosis (PVRO) systems [5–7] have been considered as a potential environmentally conscious water treatment technology for these remote locations.

Photovoltaic powered reverse osmosis (PVRO) systems are promising for community-scale applications due to

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their low-cost, small footprint, efficacy, and simple design from modular components [8]. Community-scale PVRO systems have been deployed previously in remote communities [7,9,10]. To ensure the PVRO systems serve the remote communities for their full lifetime, the systems need to be robust, since repairs can be expensive and replacement materials can be challenging to find [11–14]. One of the main challenges limiting the application of this technology to remote communities is the reliability of reverse osmosis (RO) membranes, that can be damaged by scaling, fouling or chemical degradation [15]. These effects can be minimized by selecting effective pre-treatment and cleaning methods. PVRO systems are often operated intermittently to reduce the need for batteries. Researchers have claimed intermittent operation increases membrane fouling rates and several plants with several years of operating data have shown high rates of fouling [16,17]. However, the actual impact of intermittent operation on RO membranes remains to be quantified.

1.2. Background and literature review

The RO process produces fresh water by applying a pressure higher than the osmotic pressure across a semi-permeable membrane. Water passes through the membrane producing permeate and leaves behind excess dissolved solids in a concentrated brine. RO is one of the main commercial desalination technologies due to its high energy efficiency, no thermal requirements, and modularity. The modularity allows for easy scaling and application for small, remote communities. Fig. 1 shows a schematic of a basic PVRO system typically seen in remote communities. The feed water pump transports brackish water from an intake to a simple pre-treatment system, typically a cartridge filter and anti-scalant for community-scale RO systems [7]. A high-pressure pump provides the pressure required for the reverse osmosis process. The PVRO system is powered by solar photovoltaics and the power is distributed through the system using control electronics. The permeate water is stored in a fresh water tank. In remote communities, the reject brine is typically released slowly to the environment [9].

Spiral wound membranes are the most common RO membrane type in use today. The permeate flow rate is typically described as a function of pressure, fouling, and membrane area as given by:

$$Q_P = K_W A_{mem} K_T (\Delta\bar{p} - \bar{\pi}) \quad (1)$$

where Q_P is the permeate flow rate (m^3/s), $K_W = \frac{1}{R\mu}$ is the membrane permeability for water (m s^{-1} bar^{-1}), R is the membrane resistance as function of fouling, μ is the dynamic viscosity of water, A_{mem} is the membrane surface area (m^2), K_T is the water permeability temperature correction factor, $\Delta\bar{p}$ is the average pressure applied across the membrane (bar), $\Delta\bar{\pi}$ is the average osmotic pressure applied across the membrane (bar).

The membranes can become fouled by particulates, scaling, or biological growth leading to a degradation in the performance and a decrease in membrane permeability, as shown in Fig. 2. Membrane fouling leads to increased pressure and energy requirements, reduced permeate water quality, and shorter membrane life. Some fouling can be removed by chemical cleans (reversible fouling) while some fouling will remain (irreversible fouling).

Membrane fouling is one of the major technical challenges to RO systems and as a result has been the subject of intense research over the past decades [17–26]. Biofouling and mineral scaling are two main sources of membrane fouling in operating plants [16]. Biofouling is caused by the growth of biofilm on the membrane surface [26–29]. Several researchers have performed modeling, simulations, and experiments to quantify biofouling and its influence on system parameters [25,30–32] and it remains a persistent challenge for RO systems. Scaling is caused by the precipitation of dissolved minerals onto the RO membrane and system components [34]. Scaling in brackish waters is a major concern due to the high levels of dissolved calcium carbonate and calcium sulfate often present in brackish waters, depending on the local geology. Several researchers have studied the scaling of RO membranes by calcium carbonate [34–37], silica [38–40] and iron oxides for operational conditions analogous of large-scale desalination plants. By

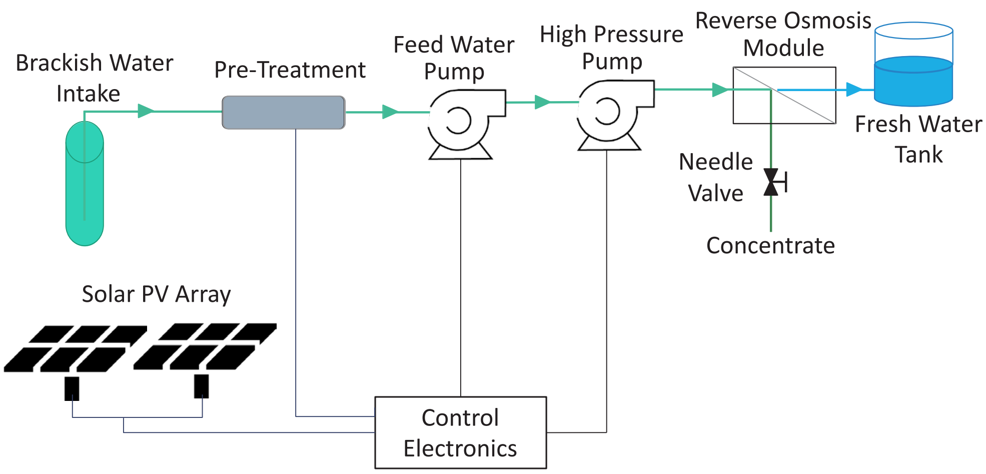

Fig. 1. Simple PVRO system schematic for remote communities, adapted from [7].

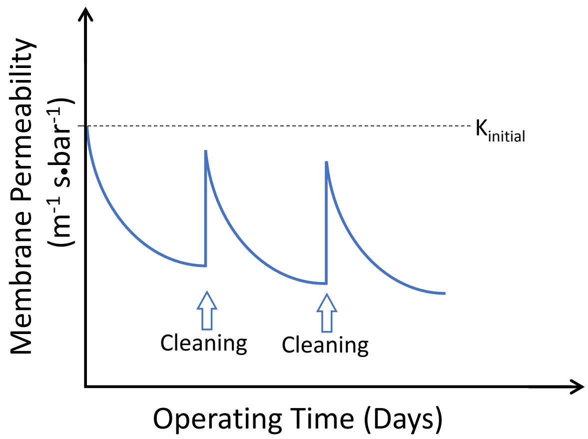

Fig. 2. Membrane permeability decreases due to fouling.

understanding fouling, designing the system appropriately, applying correct pre-treatment, and cleaning the membranes when needed, the amount of irreversible fouling (fouling that cannot be cleaned) can be minimized [42].

Fouling is a particular concern for small-scale systems in remote communities due to limited financial flexibility for membrane replacement costs, chemical cleaning costs, limited operator knowledge base, and limited resources to improve system performance by chemical or mechanical cleaning once the system is operational. Existing design methods for PVRO systems do not account for RO membrane fouling or component degradation, making robust design an important area of research [7]. An added challenge for small-scale PVRO systems in remote communities is the systems are operated intermittently to reduce the need for batteries, which are an expensive component of the system [16]. It is generally regarded that this intermittent operation leads to premature fouling and degradation of RO membranes, however, this behaviour has not been characterized [16].

1.3. Approach

This paper presents an approach for quantifying the effects of intermittent operation on membrane fouling. A custom-built experimental setup with capability to automatically test different operational conditions is described. The system is instrumented and has capability to automatically control feed flow rates, operating pressures, antiscalant dosing rates, and shutdown procedures. This system is then used to conduct preliminary studies on the effect of intermittent operation typically seen in PVRO systems. These preliminary studies were conducted using surrogate brackish water, typical of the Yucatan peninsula, with high levels of calcium sulfate. The preliminary tests indicate the experimental system is effective and can be used for characterization of operational conditions. The preliminary experimental results show there was not a significant change in membrane fouling due to the intermittent operation. Future studies are required to quantify fouling due to intermittent operation over longer time periods and the effects of operational conditions on the fouling characteristics.

2. Experimental system description

2.1. Overview

To characterize the membrane fouling typically seen in PVRO systems and the effects of different operational control strategies, a lab-scale experimental system was designed and constructed in the Water and Energy Research Laboratory (WERL) at the University of Toronto. The system is automated to systematically test different operational strategies, equipped with control valves to enable permeate rinsing, controlled dosing pumps to apply anti-scalant, and instrumented to characterize the system operation. A temperature controlled source water tank with mixing was also configured to provide consistent source water. The details of the system are described below.

2.2. System specifications

The custom bench-scale reverse osmosis system designed to test operational conditions commonly seen in PVRO systems is shown in schematic form (Fig. 3) and physical form (Fig. 4). The core of the experimental system consists of three stainless steel cross-flow (CF) reverse osmosis (RO) membrane cells (SEPA CF II, Sterlitech Corp., Kent, WA, USA) to perform the experiments in triplicate. The RO module (SEPA CF) house a flat sheet membrane of 19.1 cm ×14 cm with an active membrane area of 138.7 cm^2. The cells also allow installation of feed channel and permeate spacers to allow similar flow conditions to full scale spiral-wound membranes. This configuration uses much lower experimental water volumes (95% less water) than the smallest conventional spiral-wound reverse osmosis elements with an active area of 5570 cm^2 (DOW Filmtec™ BW30HR-2514). Flat sheet membranes (DOW Filmtec™ BW30) were cut to the appropriate shape for placement in the SEPA CF membrane element cells. A plastic feed spacer 65 mil (1651 μm) thick with diamond configuration was placed in the bottom cavity of the SEPA CF cell to provide sufficient turbulence to minimize concentration polarization. A stainless steel permeate carrier measuring 16 mil (406.4 μm) thick with diamond configuration was used above the membrane within the SEPA CF cell. As shown in Fig. 3, the system is also equipped with a circulation line with a variable valve to allow the system recovery ratio to be set to high values typical of brackish water desalination.

The water is pressurized and fed to the SEPA CF cells using a variable frequency driven (VFD) high pressure pump (Hydracell Pump Model M03SASGSSSPA, Wanner Engineering Inc., Minneapolis, MN), a pressure release valve (C46 Valve, Wanner Engineering Inc., Minneapolis, MN) and a pressure regulator to ensure the system does not exceed safe operating pressures. To remove any particulate matter, a 5 inch tall, 3 ½ inch diameter filter housing with spun polypropylene 5 μm cartridge filter (Pentek, Upper Saddle River, NJ) was installed in front of the high pressure pump. The equalization tank was used to vent air to atmosphere and to enable recirculation of the brine and experiment water to reach high recovery ratios. The float valve (Hudson Valve Inc., Bakersfield, CA) was used to refill the equalization tank with experiment water at the same rate of net water withdrawal (the three SEPA CF permeate flow rates plus the brine

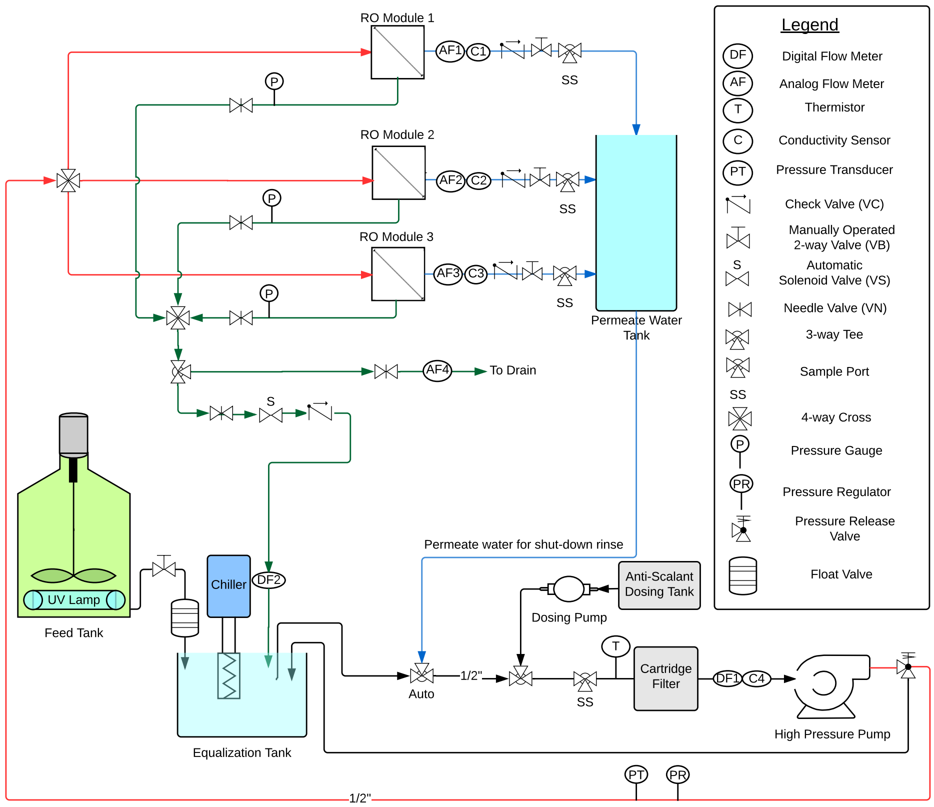

Fig. 3. Experimental system schematic with feed water tank, equalization tank and components to perform optimal cleaning procedures (auto three-way valve, dosing pump solenoid valve).

to drain flow rate). The experimental system also consists of equipment for automated rinsing, anti-scalant dosing, and start-up and shut-down procedures to be implemented in future experiments. A solenoid valve (SV3202, Omega Inc., Laval, Quebec) and an automatic three-way control valve (Electric Actuated PVC 3-Way Ball Valves – Multi-Voltage 5615, Valworx ®, Cornelius, NC) was installed for permeate rinses for future investigations. An anti-scalant dosing peristaltic pump (100.PH.030/4 Peristaltic Pump, Williamson Inc., Brighton, Sussex) was installed for accurate dosage of anti-scalant pre-treatment for future investigations.

2.3. Instrumentation and data acquisition

The types and locations of instrumentation are outlined in Fig. 3. The experimental system is equipped with four analog flow meters (FLR1000, Omega Inc., Laval, Quebec) to measure the permeate flow rate for each SEPA CF module and to measure the brine flow rate going to drain. The experimental system is also equipped with two digital flow meters (FPR301, Omega Inc., Laval, Quebec) to measure the feed flow rate and recirculation flow rate. Four inline conductivity sensors (A1002, EC/pH Sensors, Boston MA) measured the electrical conductivity, three for the permeate water (0-500 µS/cm) from each SEPA CF cell and one for the feed flow (0-5000 µS/cm). The high pressure before the SEPA CF cells was measured using a high-pressure transducer (P51-1000-S-A-I36-4.5V, SSI Technologies, Janesville,

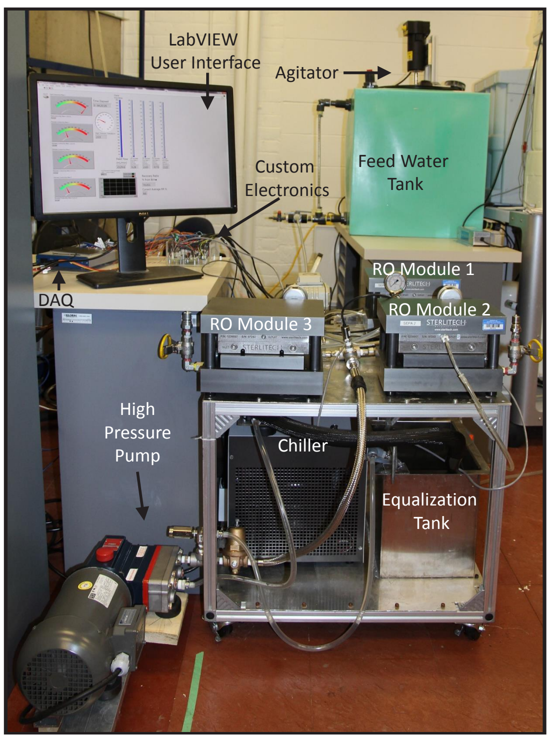

Fig. 4. Physical experimental system with user interface, experiment water tank, high pressure pump and RO modules.

WI). The temperature of the feed water was monitored using a thermistor (TH-44000-NPT Thermistor, Omega Inc., Laval, Quebec). The feed water temperature was maintained in the equalization tank using an immersion chiller (13271-500, VWR, Mississauga, Ontario) at (15 ± 1°C) analogous to source water temperature of the target community.

A data acquisition system (DAQ NI USB-6343, National Instruments) and custom electronics were used to collect the data. A high-level diagram of the electrical connections is shown in Fig. 5. Custom circuits where designed and soldered in house to interface the sensors with the data acquisition. Driver circuits were also designed for the dosing pump, feed pump, solenoid valve and three-way control valve. Custom power circuits were also configured to provide appropriate and well-conditioned power to all of the sensors and actuators.

The system control and monitoring was performed using a custom-made Labview program. Fig. 6 shows the user interface which provides online monitoring of the conductivity, temperature, pressure, flow rates, and recovery ratio. User control is also performed through this interface. For example, dosing rates of the anti-scalant can be adjusted, the three way control valve can be activated, and the system can be turned on or off. In addition, automated scripts were written to provide timing for the intermittent experiments presented below.

2.4. Water storage

Long duration experiments quantifying the fouling for small-scale PVRO systems require large volumes of experiment water. To simplify the preparation of synthetic (surrogate) experiment water and to maintain a consistent water quality throughout the duration of the experiments, a feed water tank was designed and built. The tank developed for the experimental system holds up to 190 L of water and is shown in Fig. 4. A mechanical agitator (Arrow Model 1200, Arrow Engineering Ltd., Hillside, New Jersey) was used to stir the mixture continuously throughout the experiments to ensure a constant temperature and to prevent settling of chemicals added to emulate feed water characteristics. To minimize biological contamination a UV lamp was installed. The UV lamp is automatically controlled to turn on for 30 min/d. This duration was based on an extrapolation of an analysis by Elix® which showed for 60L of Milli Q® water 10min of UV exposure/day from an in tank UV lamp was sufficient to prevent biological growth.

2.5. System improvements

Future refinements of the experimental system include the installation of a vacuum pressure gauge on the suction line of the pump to monitor the risk of pump cavitation and control of the variable frequency drive device to perform system. These changes to the system design will help ensure longevity of the experimental components and ease of system control through the computer interface. Longer duration experiments will be conducted with these improvements to fully characterize the effects of intermittency and system operational parameters.

3. Preliminary characterization of intermittent operation

3.1. Experimental overview

RO membrane scaling was investigated for intermittent and continuous operation. The water matrix was a surrogate water prepared in the lab based on the target community's water matrix. The system was operated at a high recovery of 65%, common of brackish RO systems to minimize the concentrate volume [43]. The initial experiments evaluated the impact of intermittent operation by comparing the trends in decreasing membrane permeability for the system operating for 8 h/d with the membrane permeability for the system under continuous operation. Based on operational data

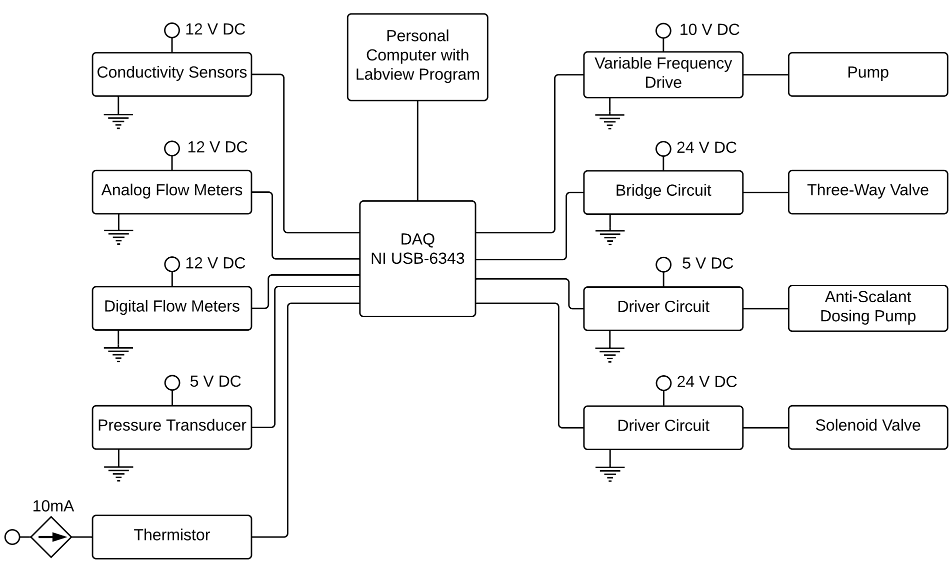

Fig. 5. Electrical system diagram with sensors, actuators, DAQ and user interface.

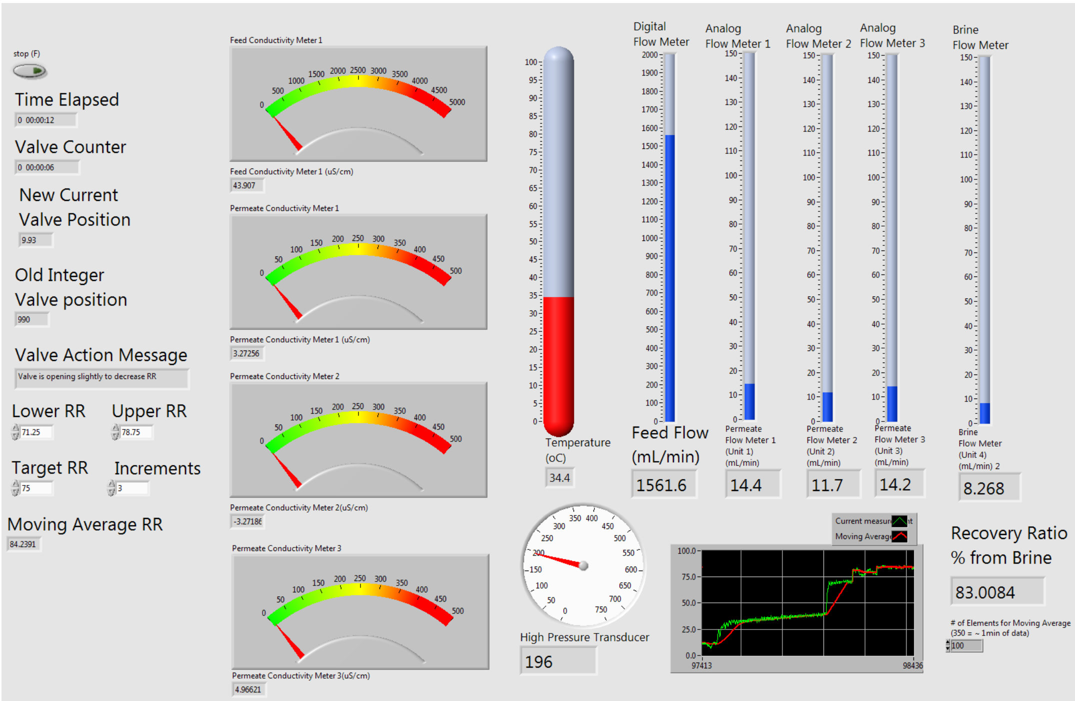

Fig. 6. Experimental system user interface programmed in Labview for real-time observation of operating parameters.

from existing renewable powered desalination plants [17], the initial hypothesis was that intermittent operation would increase the fouling rate, leading to lower membrane permeability compared to the continuously operated RO system. The main mechanism is hypothesised to be due to the membranes being in contact with stagnant water during the shutdown time, exacerbating biofouling, since biological growth would have time to colonize, and scaling, since crystal growth could occur.

3.2. Materials and methods

3.2.1. Surrogate water preparation

Due to the large volume of water required to operate a lab-scale system for ten days (approximately 600 L), synthetic (surrogate) water was used for the experiments in this study. Surrogate groundwater was prepared using inorganic salts. For these initial experiments, organics were not considered to allow easier repeatability and verification of system operation. The inorganic salts, consisting of magnesium sulfate, sodium chloride, and sodium sulfate, were purchased from Fisher Scientific Company (Fisher Chemical, Fair Lawn, New Jersey). The calcium sulfate powder was purchased from Anachemia, a VWR Company (VWR, Mississauga, Ontario). The required mass of each chemical compound was calculated to make up the water quality of the target community and dissolved into 190 L of lab grade Milli Q® water (less than 15 MΩ•cm resistivity). The lab grade water was prepared in-house using an Elix® (EMD Millipore Ltd, Etobicoke, Ontario) water purification system. A mechanical agitator (Arrow Model 1200, Arrow Engineering Ltd., Hillside, New Jersey) was used to stir the mixture at 1200 rpm for 1 h to ensure solution homogeneity. To verify that the prepared solution constituents were close to the target community water quality, a water analysis of each prepared surrogate water batch was conducted. The water analysis included electrical conductivity measured by a conductivity meter (HI98192 EC/Resistivity/TDS/Salinity meter with USP, Hanna Instruments Inc., Woonsocket, Rhode Island), turbidity measured by a turbidity meter (LTC3000 we, LaMotte, Chestertown, MD) and pH (pHH222, ph/Meter w/mv, Omega Inc., Laval, Quebec).

Surrogate water used in the experiments mimics the groundwater from the target community, La Mancalona, on the Yucatan Peninsula in Mexico. This is one of many communities with similar water and social conditions in need of a local clean drinking water source. The properties of the source water and the surrogate water are shown in Table 1. The groundwater is saline and high in dissolved minerals due to the local geology. The groundwater is nearly saturated with calcium sulfate indicating that there would be high probability of scaling in the reverse osmosis system. The mixed surrogate water matches the desired levels of dissolved minerals which influence the osmotic pressure and membrane scaling. The turbidity levels of the surrogate water are higher than the turbidity of the community's water because measurements were taken about one hour after mixing the chemicals.

3.2.2. Experimental method

To evaluate the effects of intermittent operation on membrane fouling, two separate runs were conducted. For each run, fresh membranes were installed in the SEPA cells after soaking overnight in lab grade MilliQ water. The membranes were first run in a pre-compaction cycle

Table 1
Water chemistry summary for sample from the target community of La Mancalona, Mexico [7, 43].

Ions in the water	Content in target community (mg/L)	Surrogate water (mg/L)	EPA drinking water limit (mg/L)
Sodium (Na^+)	164.20	164.2	250.0
Magnesium (Mg^{2+})	98.76	98.8	No Limit
Calcium (Ca^{2+})	502.40	502.4	No Limit
Chloride (Cl^-)	165.91	165.9	250.0
Sulfate (SO_4^{2-})	1773.24	1712.8	250.0
General characteristics	Content in target community	Surrogate water (mg/L)	EPA drinking water limit
pH	7.83	8.5	6.5–8.5
Turbidity (NTU)	0.90 NTU	3 ± 1 NTU	No Limit
Conductivity (μmhos/cm)	3770.0	2900 ± 70	No Limit
Total dissolved solids (TDS) (mg/L)	2262.0	2860 ± 40 *	500.0
Hardness (mg/L)	1661.2	1660 *	No Limit
Coliform	Present	–	0

*calculated values

with lab grade water for twenty-four hours at 13.8 bar. The intermittent run was operated for 8 h/d with 16 h of shutdown for three days. The start-up procedure was to turn on the VFD and increase the operating frequency until the system operating pressure reached 13.8 bar and slightly adjust the back pressure of the RO modules until the permeate flow rates were similar and about 8 mL/min. The recovery ratio was also adjusted using the needle valve for the waste stream (Fig. 3). After 8 h of operation the system was shut down by reducing the frequency on the VFD to zero. To compare the membrane fouling to a continuous run, the system was operated continuously for 24 h. This is the runtime for the intermittent experiments to enable a fair comparison between operating modes. A new set of membranes were prepared in the same process (soaked overnight and pre-compacted for 24 h) and used in the continuous run. The system operating pressure vs. time for intermittent operation (Fig. 7a) and for continuous operation (Fig. 7b).

3.3. Preliminary experimental results and discussion

Using the measured product flow rates, the operating pressure, and feed water conductivity, the membrane permeability was calculated. The filtered permeability data set for the intermittent run, shown in Fig. 8, was averaged for each thirty minutes of operation. The hours when the experimental system was shut down are not included. The pressure regulator was engaged during the intermittent experimental run and continuous experimental run maintaining a consistent transmembrane pressure (Fig. 9). The recovery ratio was also maintained at an average recovery ratio of 80% (Fig. 10) though there was considerable variation for the intermittent experimental run due to slight manual adjustments using the needle valve. Overall, in Fig. 8 there is a consistent trend of decreasing permeability. For the intermittent run, there is a rapid decrease in membrane permeability that is seen immediately after the first time the system was shutdown for 16 h (seen in Fig. 8 at hour eight). The permeability decreased rapidly to below 4 $m^{-1}s\ bar^{-1}$ by the end of 24 h of intermittent operation.

In general, there is an initial increase in the permeability after start-up and then a decrease in permeability. The initial increase in permeability is anticipated to be due to the rapid removal of salts that had accumulated on the surface of the membrane during the time when the system was shutdown. The slow decrease is likely due to the fouling during the operating time from scaling, cake resistance, and biofouling. It can be seen that the permeability in SEPA 1 dropped less rapidly than in SEPA 2 and SEPA 3. This indicates a lower rate of fouling on SEPA 1's membrane. This could be due to unit to unit variation or due to an unequal division of flow in the piping flow manifold. Future experiments and refinements of the experimental system design will study this effect.

The preliminary continuous experimental run was operated for approximately 24 h. Fig. 11 shows the calculated membrane permeability for the continuous experimental run. The membrane permeability decreases during continuous operation. The membrane permeability for SEPA 2 and SEPA 3 show a similar trend of decline. SEPA 1 has a distinctive pattern of decline with a sharp linear decrease starting at the sixth hour of the experiment, the permeability declined at a steeper rate than SEPA 2 and 3 from this point onwards to a minimum at the 24th hour of the experiment. The rapid sharp decline in permeability for SEPA 1 may have been caused from unequal division of flow in the parallel manifold or from a rapid fouling of the membrane in SEPA 1. The pressure throughout the experiment was very stable because the pressure regulator was engaged from the beginning of the experiment, as shown in Fig. 9. The needle valves which pressurize the SEPA cells were set initially when all three SEPA cells had a similar permeability and were not adjusted throughout the duration of the experiment.

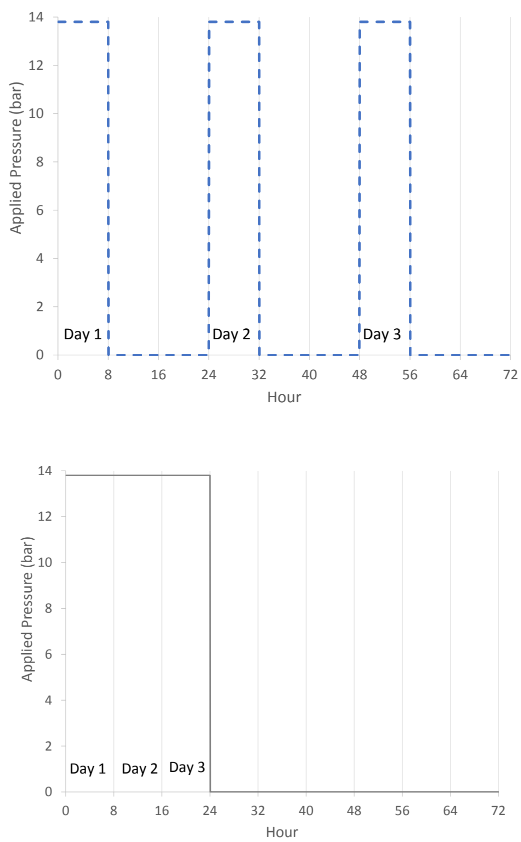

Fig. 7. Operating pressure for the intermittent experimental run (a) and the continuous experimental run (b).

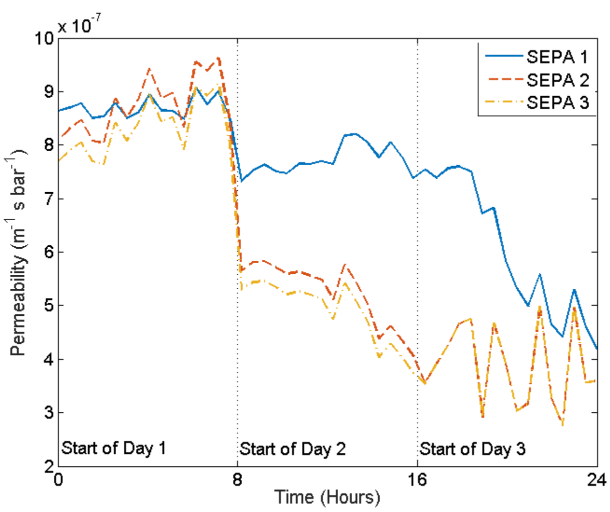

Fig. 8. Membrane permeability as a function of operating time for the intermittent run (averaged over 30 min intervals). The hours when the system was shutdown are not included.

A comparison of the preliminary intermittent and continuous run is shown in Fig. 12. Comparing the calculated permeability values, there is a significant difference between the two operating conditions. This could be due to the severe pressure fluctuations observed for the intermittent run compared to the continuous run. As well, the average recovery ratio for the intermittent run was 80% with minimal variation (Fig. 10), while for the continuous run it was on average 80% but with larger variations (Fig. 10). Despite these variations, the preliminary results indicate that increased fouling due to scaling for intermittent operation may not be as significant as anticipated. Initial experimental tests showed large variations between the SEPA cells, and this current setup has resolved large variations. However, small variations still exist between SEPA cells due to variability between the membrane fouling rate. This variability motivated performing the experiments in triplicate. Future studies with an improved experimental setup to ensure a consistent recovery ratio and pressure will be performed to quantify the difference in fouling rates between the intermittent and continuously operated systems.

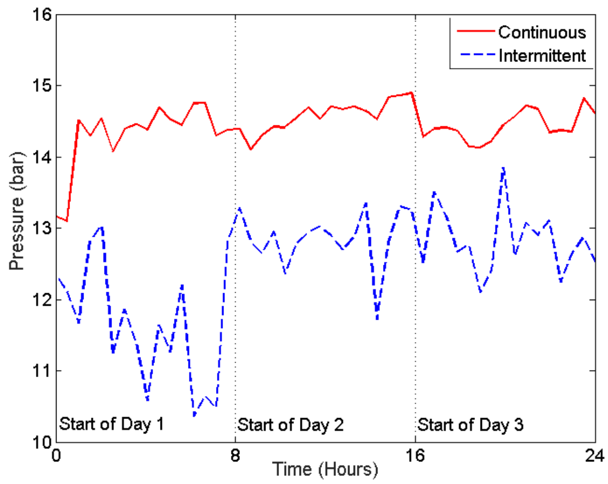

Fig. 9. Transmembrane pressure in bar for the intermittent and continuous experimental run.

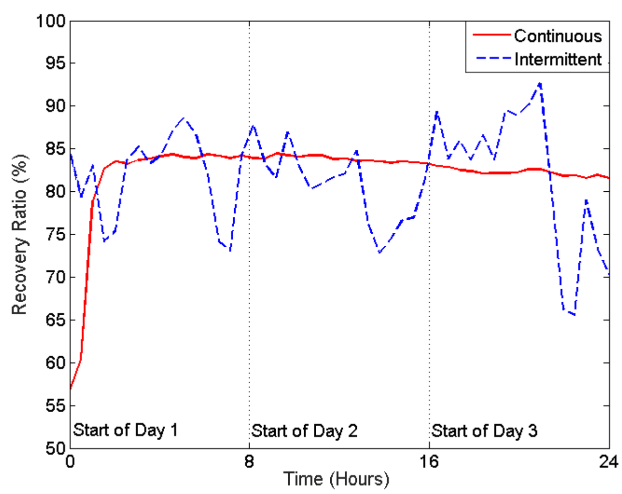

Fig. 10. Comparison of the recovery ratio for the continuous and intermittent run.

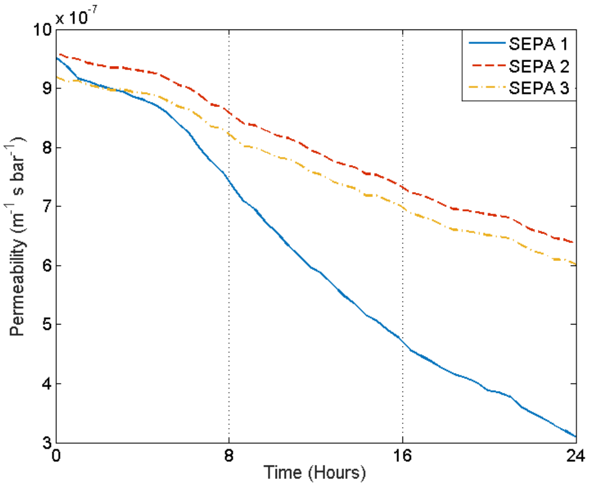

Fig. 11. Membrane permeability vs. operating time for the continuous run (averaged over 30 min intervals).

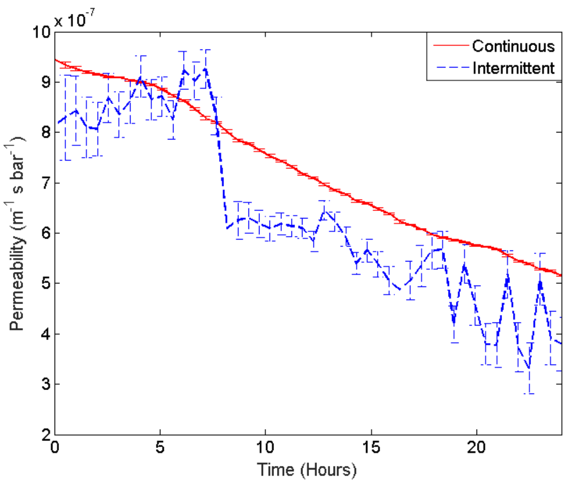

Fig. 12. Comparison of preliminary continuous and intermittent experiments.

4. Summary and Conclusions

This paper presents an approach to evaluate the effects of intermittent operation on membrane fouling in PVRO systems, which had never been previously quantified. To evaluate this effect, a custom experimental system has been designed and constructed. The system consists of three stainless steel SEPA cross-flow reverse osmosis membrane cells connected in parallel, and is equipped with computer-controlled valves and pumps to autonomously test different operating conditions. The system is also instrumented with pressure, flow, temperature, and conductivity sensors to characterize membrane fouling.

Preliminary experiments were conducted using the system to evaluate the effects of intermittent operation for brackish water with minimal organic contamination. It was found in these preliminary experiments that the intermittent operation did not have significant impact on membrane permeability. These experiments contradict previous unverified claims that membrane fouling is greatly accelerated by intermittent operation. However, it should be noted that these experiments were only conducted for a short period of time, with minimal organic water content and at different recovery ratios. It is hypothesised that the intermittent operation increases fouling by two main mechanisms: scaling and biofouling. Scaling is hypothesised to be increased overall for the intermittent operation since the water is stagnant existing nucleation sites can have substantial time for crystal growth. Although biological content was kept to a minimum through the use of the UV lamp in the experiment water tank, there is evidence when the flow meters were disassemble that there is biological growth in the system. When the water is stagnant overnight it undoubtedly interacts with the air and biological content can grow during the shutdown period. Future work will evaluate the mechanisms behind the fouling for intermittent operation and the effects of intermittent operation over a longer time period. In addition, the experimental system will be used to examine online approaches to identify when membrane scaling or biofouling is occurring and apply corrective actions, such as anti-scalant dosage or system cleaning cycles.

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Symbols

Q_p — Permeate flow rate (m^3/s)

$K_W = \frac{1}{R\mu}$ — Membrane permeability for water ($m\ s^{-1}\ bar^{-1}$)

R — Membrane resistance as function of fouling

μ — Dynamic viscosity of water

A_{mem} — Membrane surface area (m^2)

K_T — Water permeability temperature correction factor

$\Delta\bar{p}$ — Average pressure applied across the membrane (bar)

$\Delta\bar{\pi}$ — Average osmotic pressure applied across the membrane (bar)

References

[1] World Health Organization and Unicef Joint Monitoring Program (JMP), Progress on Sanitation and Drinking Water: 2014 Update, Geneva, Switzerland, 2014.

[2] G. Legros, I. Havet, N. Bruce, S. Bonjour, The energy access situation in developing countries, New York, 2009. http://www.

undp.org/content/dam/undp/library/Environment and Energy/Sustainable Energy/energy-access-situation-in-developing-countries.pdf.
[3] H. Morais, P. Kádár, P. Faria, Z.A. Vale, H.M. Khodr, Optimal scheduling of a renewable micro-grid in an isolated load area using mixed-integer linear programming, Renew. Energy., 35 (2010) 151–156.
[4] A.A. Setiawan, Y. Zhao, C. V. Nayar, Design, economic analysis and environmental considerations of mini-grid hybrid power system with reverse osmosis desalination plant for remote areas, Renew. Energy., 34 (2009) 374–383.
[5] F. Vince, F. Marechal, E. Aoustin, P. Bréant, Multi-objective optimization of RO desalination plants, Desalination., 222 (2008) 96–118.
[6] M.M. El-Halwagi, Synthesis of reverse-osmosis networks for waste reduction, AIChE J., 38 (1992) 1185–1198.
[7] A. Bilton, A modular design architecture for application to community-scale photovoltaic-powered reverse osmosis systems, PhD, Massachusetts Institute of Technology, 2013. http://dspace.mit.edu/bitstream/handle/1721.1/79337/845073888.pdf?sequence=1.
[8] P. Poovanaesvaran, M.A. Alghoul, K. Sopian, N. Amin, M.I. Fadhel, M. Yahya, Design aspects of small-scale photovoltaic brackish water reverse osmosis (PV-BWRO) system, Desalin. Water Treat., 27 (2011) 210–223.
[9] B. Peñate, V.J. Subiela, F. Vega, F. Castellano, F.J. Domínguez, V. Millán, Uninterrupted eight-year operation of the autonomous solar photovoltaic reverse osmosis system in Ksar Ghilène (Tunisia), Desal. Water Treat., 55(11) (2015) 3141–3148.
[10] B.G. Keefer, R.D. Hembree, F.C. Schrack, Optimized matching of solar photovoltaic power with reverse osmosis desalination, Desalination, 54 (1985) 89–103.
[11] L. Kelley, H. Elasaad, S. Dubowsky, Autonomous operation and maintenance of small-scale PVRO systems for remote communities, Desal. Water Treat., 55(10) (2015) 2843–2855.
[12] A. Al-Karaghouli, D. Renne, L.L. Kazmerski, Technical and economic assessment of photovoltaic-driven desalination systems, Renew. Energy., 35 (2010) 323–328.
[13] S. Dallas, N. Sumiyoshi, J. Kirk, K. Mathew, N. Wilmot, Efficiency analysis of the Solarflow – An innovative solar-powered desalination unit for treating brackish water, Renew. Energy., 34 (2009) 397–400.
[14] A.I. Schafer, C. Remy, B.S. Richards, Performance of a small solar-powered hybrid membrane system for remote communities under varying feedwater salinities, Water Sci. Technol. Water Supply., 4 (2004) 233–243.
[15] B. Durham, A. Walton, Membrane pretreatment of reverse osmosis: Long-term experience on difficult waters, Desalination, 122 (1999) 157–170.
[16] J.L. Lienhard, M.A. Antar, A. Bilton, A. Blanco, G. Zaragoza, Solar Desalination, Annu. Rev. Heat Transf., 15 (2012) 277–347.
[17] A. Cipollina, E. Tzen, V. Subiela, M. Papapetrou, J. Koschikowski, R. Schwantes, Renewable energy desalination: performance analysis and operating data of existing RES desalination plants, Desal. Water Treat., 55 (2015) 3126–3146.
[18] A.G. Pervov, Scale formation prognosis and cleaning procedure schedules in reverse osmosis systems operation, Desalination, 83 (1991) 77–118.
[19] E. Lyster, M.M. Kim, J. Au, Y. Cohen, A method for evaluating antiscalant retardation of crystal nucleation and growth on RO membranes, J. Memb. Sci., 364 (2010) 122–131.
[20] S. Sobana, R.C. Panda, Modeling and control of reverse osmosis desalination process using centralized and decentralized techniques, Desalination, 344 (2014) 243–251.
[21] G. Greenberg, D. Hasson, R. Semiat, Limits of RO recovery imposed by calcium phosphate precipitation, Desalination, 183 (2005) 273–288.
[22] T. Nguyen, F.A. Roddick, L. Fan, Biofouling of water treatment membranes: a review of the underlying causes, monitoring techniques and control measures., Membranes (Basel), 2 (2012) 804–840.
[23] M.D. Afonso, J.O. Jaber, M.S. Mohsen, Brackish groundwater treatment by reverse osmosis in Jordan, Desalination, 164 (2004) 157–171.
[24] A.A. Alawadhi, Pretreatment plant design — Key to a successful reverse osmosis desalination plant, Desalination, 110 (1997) 1–10.
[25] Z. Hu, A. Antony, G. Leslie, P. Le-Clech, Real-time monitoring of scale formation in reverse osmosis using electrical impedance spectroscopy, J. Membr. Sci., 453 (2014) 320–327.
[26] A.I. Radu, J.S. Vrouwenvelder, M.C.M. van Loosdrecht, C. Picioreanu, Modeling the effect of biofilm formation on reverse osmosis performance: Flux, feed channel pressure drop and solute passage, J. Membr. Sci., 365 (2010) 1–15.
[27] R.A. Al-Juboori, T. Yusaf, Biofouling in RO system: Mechanisms, monitoring and controlling, Desalination, 302 (2012) 1–23.
[28] M. Herzberg, M. Elimelech, Biofouling of reverse osmosis membranes: Role of biofilm-enhanced osmotic pressure, J. Membr. Sci., 295 (2007) 11–20.
[29] F.A.A. El Aleem, M.I. Alahmad, Biofouling problems in membrane processes for water desalination and reuse in Saudi Arabia, Int. Biodet. Biodegrad., 41 (1998) 19–23.
[30] A. Matin, Z. Khan, S.M.J. Zaidi, M.C. Boyce, Biofouling in reverse osmosis membranes for seawater desalination: Phenomena and prevention, Desalination, 281 (2011) 1–16.
[31] J.S. Vrouwenvelder, C. Picioreanu, J.C. Kruithof, M.C.M. van Loosdrecht, Biofouling in spiral wound membrane systems: Three-dimensional CFD model based evaluation of experimental data, J. Membr. Sci., 346 (2010) 71–85.
[32] A.I. Radu, J.S. Vrouwenvelder, M.C.M. van Loosdrecht, C. Picioreanu, Effect of flow velocity, substrate concentration and hydraulic cleaning on biofouling of reverse osmosis feed channels, Chem. Eng. J. 188 (2012) 30–39.
[33] S.R. Suwarno, X. Chen, T.H. Chong, V.L. Puspitasari, D. McDougald, Y. Cohen, S.A. Rice, A.G. Fane, The impact of flux and spacers on biofilm development on reverse osmosis membranes, J. Membr. Sci. 405–406 (2012) 219–232.
[34] S.H. Joo, B. Tansel, Novel technologies for reverse osmosis concentrate treatment: A review, J. Environ. Manage., 150 (2015) 322–335.
[35] T. Chen, A. Neville, M. Yuan, Calcium carbonate scale formation – Assessing the initial stages of precipitation and deposition, J. Pet. Sci. Eng., 46 (2005) 185–194.
[36] L.F. Greenlee, F. Testa, D.F. Lawler, B.D. Freeman, P. Moulin, The effect of antiscalant addition on calcium carbonate precipitation for a simplified synthetic brackish water reverse osmosis concentrate, Water Res., 44 (2010) 2957–2969.
[37] Z. Amjad, Applications of antiscalants to control calcium sulfate scaling in reverse osmosis systems, Desalination, 54 (1985) 263–276.
[38] E. Lyster, J. Au, R. Rallo, F. Giralt, Y. Cohen, Coupled 3-D hydrodynamics and mass transfer analysis of mineral scaling-induced flux decline in a laboratory plate-and-frame reverse osmosis membrane module, J. Membr. Sci., 339 (2009) 39–48.
[39] S. Salvador Cob, C. Beaupin, B. Hofs, M.M. Nederlof, D.J.H. Harmsen, E.R. Cornelissen, A. Zwijnenburg, F.E. Genceli Güner, G.J. Witkamp, Silica and silicate precipitation as limiting factors in high-recovery reverse osmosis operations, J. Membr. Sci., 423–424 (2012) 1–10.
[40] G. Braun, W. Hater, C. Zum Kolk, C. Dupoiron, T. Harrer, T. Götz, Investigations of silica scaling on reverse osmosis membranes, Desalination, 250 (2010) 982–984.
[41] M. Badruzzaman, A. Subramani, J. DeCarolis, W. Pearce, J.G. Jacangelo, Impacts of silica on the sustainable productivity of reverse osmosis membranes treating low-salinity brackish groundwater, Desalination, 279 (2011) 210–218.
[42] S.P. Chesters, M.W. Armstrong, M. Fazel, R. Wilson, D.A. Golding, RO Membrane Cleaning, Past, Present, Future – Innovations for Improving Ro Plant Operating Efficiency, Int. Desalin. Assoc. World Congr. Desal. Water Reuse, 2013.
[43] R.Y. Ning, Pretreatment for Reverse Osmosis Systems, in: R.Y. Ning (Ed.), Expand. Issues Desalin., 2011: pp. 57–62.