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Investigation of environmental influences on membrane biofouling in a Southern California desalination pilot plant

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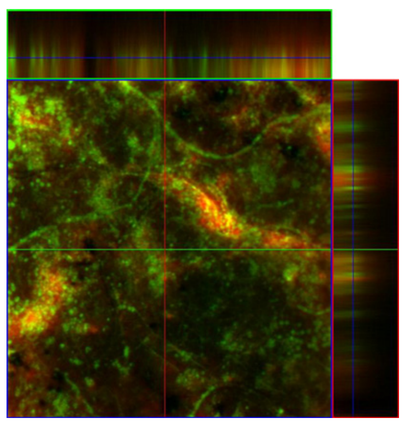
HIGHLIGHTS

- This study develops a seawater membrane desalination biofouling indicator.
- Membrane performance was related to environmental and water quality parameters.
- Turbidity and SDI are inadequate to indicate membrane performance decline.
- We identify chlorophyll as a sensitive indicator for membrane biofouling.
- We show membrane fouling monitor is a useful tool for biofouling analysis.

GRAPHICAL ABSTRACT



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ABSTRACT

One of the challenges the seawater desalination industry faces today is reverse osmosis (RO) membrane biofouling. Traditional water quality parameters such as SDI and the RO feed water turbidity are inadequate at protecting the membrane from biofouling. This research investigated the environmental and water quality parameters in a Southern California desalination plant in order to develop a set of seawater desalination RO membrane biofouling indicators. Statistical analysis was performed on data collected onsite over two years. The relationships between operation parameters, rain precipitations, TOC, UV_{254}, chlorophyll fluorescence in raw seawater and the performance loss of the RO desalination process are presented. The environmental triggers for accelerated RO membrane biofouling was further investigated by developing membrane fouling simulators at the desalination pilot plant. Biofouling was confirmed by confocal laser scanning microscopy investigation of membrane biofilm and live and dead bacterial cell counts. The results of this study indicated that biofouling was significantly correlated with water quality changes. Thus, chlorophyll fluorescence measurements can be used as a precursor for desalination membrane biofouling.

Abbreviations: CLSM, Confocal Laser Scanning Microscope; DOC, dissolved organic carbon; EPS, extracellular polymeric substances; MF, microfiltration; NDP, net driving pressure; NTU, Nephelometric turbidity unit; RO, reverse osmosis; SDI, silt density index; SWRO, seawater reverse osmosis; TEP, Transparent extracellular polysaccharides; TOC, total organic carbon; UF, ultrafiltration.

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1. Introduction

One of the challenges the seawater desalination industry faces today is RO membrane fouling. Depending on its severity, it may have a measurable impact on the economics and reliability of freshwater production by desalination. The advances in pretreatment technologies, i.e. microfiltration and ultrafiltration, although have significantly reduced the inorganic fouling, organic and biofouling continue to plague desalination industry. Biofouling is caused by biofilm formation on the RO membrane surface by bacteria and their metabolites that naturally occur in the feed seawater. Biofilm is an organic film composed of live and dead microorganisms embedded in a polymer matrix, consisting of extracellular polymeric substances (EPS) such as polysaccharides, proteins and lipids [1]. The biofilm formation on the membrane surface increases the pressure needed for maintaining steady production of freshwater by the membrane elements [2]. In order to compensate for loss of productivity due to biofouling, the feed pressure of the seawater RO (SWRO) membrane system would need to be increased, which in turn would result in elevated energy requirement to produce the same volume of freshwater.

Currently, seawater pretreatment methods such as oxidant-based disinfection, ultraviolet irradiation, and coagulation followed by granular media or membrane filtration can reduce the number of bacteria in the RO feed seawater significantly, but would typically not eliminate biofilm formation on the RO membranes [3]. Empirical experience from desalination plants' operators reveal that SWRO membrane fouling follows a seasonal cycle, which implies that environmental and water quality factors have strong influences on the membrane fouling potential.

Previous studies on water reuse RO membrane biofouling suggest that the growth of biofilm-forming bacteria is dependent on the concentration of dissolved organic carbon (DOC) as energy and carbon sources in feed water [4]. However, typical seawater has a much lower concentration of DOC than natural freshwater and treated wastewater for reuse, and the effect of low concentration of organic nutrient on the establishing biofilm and the growth of biofilm-forming microorganisms in seawater has not been well documented. Recent studies in biofilm-forming microorganisms on the SWRO membrane [5–7] revealed that the seawater biofouling microorganisms were very different than those in the wastewater and freshwater environment, and that these bacteria may respond to different triggers in the environment. So far, there were few attempts to investigate the correlation between the biofilm build up rate and the SWRO membrane operating parameters and the feed water quality index. Yet understanding such relationships may hold the key to predict and control the biofouling event. A readily available biofouling indicator can trigger preventive cleaning and regeneration of membrane productivity.

This study collected environmental and water quality parameters in a Southern California desalination plant and presented statistical analysis of relationships between rain precipitations, total organic carbon (TOC), chlorophyll fluorescence in raw seawater and the performance loss of RO desalination process. The environmental triggers for accelerated RO membrane biofouling was further investigated by developing and deploying membrane fouling simulators at the desalination pilot plant. The results of this study indicated that biofouling was significantly correlated with water quality changes. Chlorophyll measurements can be used as a precursor for desalination membrane fouling.

2. Materials and methods

2.1. Desalination plant operation data

The study was conducted at Carlsbad desalination pilot plant, a co-generation plant in north San Diego County, California. The facility uses the discharging seawater from Encinitas Power Plant's cooling system as the intake water. As a result, the temperature of the intake water fluctuates significantly depending on the operation of the power plant. The pilot plant uses HYDRAcap Capillary Ultrafiltration Modules (Hydranautics, Oceanside, California) as the pretreatment of the SWRO process. The UF membrane surface polymer is hydrophilic polyethersulfone with nominal molecular weight cutoffs (MWCO) of 150 kDa to produce permeate turbidity of <0.07 NTU. The SWRO system has two stages. Each stage has 2 pressure vessels containing 3 spiral-wound SWC5 RO membrane elements (Hydranautics). The typical recovery of the plant was 50%, and the permeate flow rate was between 2.3 and 4.6 $m^3 \cdot h^{-1}$ during normal operation. No chemical cleaning was performed during the test period. The pilot plant only conducted RO system flushing with RO permeate on a regular basis.

To indicate the loss of RO membrane performance due to fouling, we compared the membrane performance of the aged membrane with that of the new membrane, termed fouling indicator (FI). FI is computed as: $FI = R/R_{new}$; where R is the resistance of the membrane that has been in operation for greater than 1 week; R_{new} is the average resistance of a new membrane that has been in operation for less than 1 week. The membrane resistance R is computed using: $R = (NDP \times TCF)/Flux$, where NDP is net driving pressure, TCF is temperature correction factor and $Flux$ is permeate flux. Based on FILMTEC Elements Technical Manual [8], NDP is calculated using the following equation:

$$NDP = P_f - \frac{\Delta P_{fc}}{2} - P_p - \pi_f \left[\frac{C_{fc}}{C_f} p_f - (1-R) \right]$$

Where P_f is feed pressure, ΔP_{fc} is concentrate-side pressure drop, P_p is permeate pressure, π_f is feed osmotic pressure, C_{fc} is average concentrate-side concentration, C_f is feed concentration, p_f is concentration polarization factor, and R is salt rejection fraction.

The empirical TCF for $T \leq 25$ °C as defined by FILMTEC [8] $TCF = e^{2640 \times \left(\frac{1}{298} - \frac{1}{T+273}\right)}$ is used in the study because water temperature never exceed 25 °C at the study site. R_{new} was found to be 0.059 $kPa \cdot m^{-1} \cdot s$ through calculation of the first week operation data of new membranes. FI is unit-less because it is the ratio of two R in $kPa \cdot m^{-1} \cdot s$. Plant operation parameters including RO feed pressure, temperature, conductivity and flux were collected from daily data logger.

The study was carried out in two phases. Phase I study analyzed pre-recorded plant operation data provided by the operator, encompassing the period between January 2008 and April 2009. In addition to SWRO performance indicator (FI), UF silt density index (SDI) and raw water turbidity (NTU) from the plant operation record were obtained and used in the data analysis. Water pH during the study period were constant and they were not included in the final analyses. Water conductivity was included in the computation of NDP as the component of feed osmotic pressure. The phase II study was carried out between July 2010 and July 2011, and all operation and water quality parameters were collected in real time. In addition to the UF SDI and raw water NTU, UF filtrate turbidity, raw water UV_{254} absorbance (Hach, Loveland, Colorado) were also taken onsite during the phase II study.

2.2. Environmental and water quality data

To better characterize the relationship between the SWRO performance and environmental factors, additional environmental data including daily rain precipitation, chlorophyll fluorescence, and TOC were collected. Daily precipitation data were retrieved from a local weather station in Carlsbad (KCACARLS5) from www.wunderground.com for both phase I & II studies. Chlorophyll fluorescence from Scripps Institute of Oceanography (SIO) Pier were used as the approximation of the concentrations at the pilot plant for phase I study since no real time measurement was conducted onsite. SIO pier is located approximately