ARTICLE IN PRESS

Desalination xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Desalination

journal homepage: www.elsevier.com/locate/desal

A review of fouling indices and monitoring techniques for reverse osmosis

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ARTICLE INFO

Keywords:
Reverse osmosis
Membrane fouling
Fouling sensing methods
On- and off-line fouling detection
Fouling potential assessment

ABSTRACT

This paper reviews the methods to monitor reverse osmosis (RO) membrane fouling, either by characterizing the fouling potential of the feed or by detecting the fouling condition of the membranes. The suitability for on-line monitoring is discussed. The available methods to determine fouling propensity of the RO feedwater are based on fouling by particulates, scalants, organics and biofilms. For particulate fouling a range of indices have been developed based on the filterability of the feed; indices for scaling potential rely on inorganic species analysis. For organic and biofouling potential there are a range of analyses of total and specific organic components. While most of the fouling potential methods involve off-line characterization, some are amenable to on-line detection. To monitor the state of an RO process, sensors can be directly installed on a spiral wound module (in-situ) or on a side stream (ex-situ) 'canary' cell that simulates the plant operation. The available techniques, critically reviewed in this paper, can be incorporated into the RO process to provide information on the nature of the foulants deposited on the membrane. These techniques provide on-line observation, some of which are suitable for large scale plants and others are more suited for basic research.

1. Introduction

Reverse osmosis (RO) technology plays a vital role in water desalination and wastewater reclamation to meet the ever-increasing water demand. However, the effectiveness of this technology is compromised by fouling of the membranes. Fouling impacts the performance, which results in an increase in the energy demand, cleaning frequency and consumption of chemicals, membrane replacements and hence the cost of the water treatment. Thus, it is critical to mitigate or prevent fouling in order to improve RO technology. The purpose of monitoring is to provide information that allows actions to limit the degree of fouling or preferably to pre-empt fouling.

Fig. 1 shows that monitoring can determine either the 'fouling propensity' of the feed or the 'state of the membrane'. Assessing the fouling propensity involves sampling and characterizing the feed solution. In most cases this requires off-line analysis; however, some properties can be monitored on-line. To monitor the state of the membrane typically involves an on-line non-invasive observation technique to characterize deposits on the membrane surface. The membranes monitored could be part of a production cascade or can be installed on side-stream simulators (known as 'canary' cells – see below).

Fouling propensity monitoring is based on the fact that the foulants present on the membrane must originate from the components in the feedwater whose concentration determines the degree of fouling in the RO modules. Information on the type and amount of foulants that are present in the feed offers several advantages: (i) mitigation strategies can be performed to reduce the amount of foulants fed to the RO, such as diverting the feed flow or plant shutdown to prevent severe damage to the RO membranes; (ii) control strategies can be employed to minimize fouling such as regulating the dosing of antiscalants or biocides; (iii) the long term performance of an RO process can be predicted and a cleaning schedule can be recommended; (iv) assisting in the selection of an appropriate pre-treatment method in order to meet the criteria set by the RO manufacturers and (v) providing a tool to assess the efficiency of pre-treatment stages prior to the RO system.

Monitoring the fouling state of the membrane involves using sensors that can respond to the fouling deposits on the RO membrane and detect incipient fouling. This can be done by applying these sensors directly on a spiral wound module (SWM), known as "in-situ" observation. The fouling detection can also be done by installing an RO fouling monitor cell onto a RO train or a "canary cell" on a side stream to an RO train [1], known as "ex-situ" observation. The canary cell mimics the hydrodynamics in the RO modules and thus will experience similar

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https://doi.org/10.1016/j.desal.2017.12.009
Received 18 May 2017; Received in revised form 6 December 2017; Accepted 6 December 2017
0011-9164/

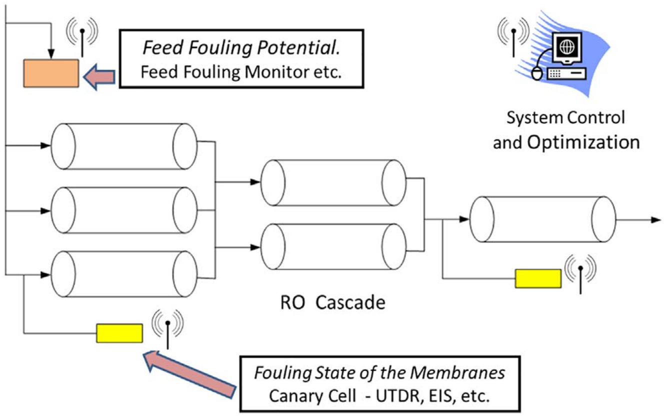

Fig. 1. Monitoring for fouling detection and control.

fouling. As such, fouling conditions in a SWM can be estimated via a canary cell. There are different types of non-invasive monitoring techniques that can be easily used in this canary cell or applied directly on a SWM to assess the fouling conditions, for example, ultrasonic time-domain reflectometry (UTDR) and electrical impedance spectroscopy (EIS). In this review the looser definition for non-invasive fouling monitoring techniques refer to methodologies that have negligible disturbance to the process operation while being able to assess fouling conditions of the membranes. However some techniques involve the use of detectors located within the membrane module or introduction of tracer. These methods have minimal disturbance to the process, we refer to them as quasi non-invasive. Prior reviews of non-invasive observation techniques used in membrane fouling studies are available [2,3].

Several reviews have been published on mitigating and detecting fouling and scaling in RO membrane processes that include the development of antifouling RO membranes for water treatment [4,5], the state-of-the-art of RO [6–8], fouling-related problems on RO membranes [9–12], RO transport models [13,14], and RO pre-treatment strategies [15]. This paper complements these prior reviews by providing a comprehensive overview of the different types of RO fouling monitoring methods that are classified into two categories: those for assessing the fouling propensity of RO feedwaters; and (2) those for monitoring the fouling of an RO process. A brief overview of the different types of RO fouling is given in Section 2 that provides a fundamental understanding of type of fouling that can occur in an RO plant. This review also includes a table that summarizes the types of fouling monitors and their unique features.

2. Types of fouling

For salt rejecting membrane such as RO and NF, the accumulation of solute or particles on the membrane surface by convection is an inevitable phenomenon, known as the concentration polarization effect [16]. The rejected solute or particles that accumulated near or on the membrane surface could have one of several fates. For example, some solute or particles could remain as individual entities in this concentrated layer, which could either due to the repulsive forces between solute or particles or the concentration of the solute or particles is low. However, when the solute/particles accumulated to higher concentration, some solute or particles could interact with each other or membrane surface that lead to the formation of a more "structured" layer, typically known as cake layer formation. These "structured" layers are either reversible and could be removed by increased hydrodynamic regime or irreversible that requires chemical cleaning regime for their removal. There are various types of fouling processes encountered in a RO system, namely (i) particulate/colloidal fouling; (ii) scaling; (iii) organic fouling; and (iv) biofouling. The types of RO fouling greatly depend on the source of water. Autopsy studies performed by Khan et al. [17] showed that the fouling types and mechanisms were different between seawater RO (SWRO) and wastewater RO (WWRO). In their study they performed autopsies on SWRO and WWRO RO SWMs (lead and terminal modules) after three months and five months of operation. Their autopsy results revealed that the lead elements in the WWRO train were mainly fouled by bio/organic matter, whereas inorganic fouling was observed on the terminal position element. Interestingly, SWRO had bio/organic fouling at both the lead and terminal elements [17].

Fouling in RO leads to a decrease in the water permeability (flux divided by the applied pressure) that is observed as a decline in flux at constant pressure or an increase in applied pressure at constant flux. The foulants can cause a decrease in the permeability by, (i) providing an additional hydraulic resistance, $R_{F,}$ (ii) partially blocking the available membrane surface (typical of scaling) or (iii) exacerbating concentration polarization by providing an 'unstirred' layer that causes what is referred to as cake-enhanced concentration polarization (CECP) that leads to cake-enhanced osmotic pressure (CEOP) effects (see Section 2.1).

2.1. Particulate/colloidal fouling

Colloids are a major class of foulants that cause serious problems for RO membranes. They are usually small enough to pass through most of the pre-treatment process, yet large enough to be retained and accumulated on the RO membrane surface, thereby causing severe fouling [8]. Researchers [18,19] have shown that colloidal solids having a small size are primarily responsible for colloidal fouling. Larger colloids do not foul as much because of the hydrodynamic lift effect owing to the cross-flow velocity profile near the membrane surface. Examples of colloidal foulants include clay, iron oxide and, silica particles, macromolecules such as proteins, polysaccharides and organic matter, bacteria and viruses (bio-colloids). These colloids typically lie in the size range of 1–1000 nm; however, there are no well-defined limits [20,21]. Colloidal fouling in RO has been extensively studied over the years as summarized in two review articles [22,23].

Numerous studies have addressed another fouling mechanism that causes flux decline owing to the presence of colloids [24–28]. As the colloids accumulate on the membrane surface and trigger the formation of a cake layer, the back-diffusion of salt ions is hindered by this colloidal cake layer. Consequently, the concentration of the salt ions near the membrane surface is elevated. This newly identified fouling mechanism for salt-rejecting membranes was referred to as the cake-enhanced osmotic pressure (CEOP) effect by Hoek and Elimelech [26]. The CEOP effect not only causes the flux decline or TMP increase during colloidal filtration, but also creates conditions conducive for salt ions to permeate through the membrane; hence, the salt rejection decreases as the filtration proceeds. In fact, CEOP contributes more to the major performance loss than the hydraulic resistance contributed by the cake layer deposition [27]. Note that the CEOP increases with cake thickness and the salinity of the feed [25].

2.2. Scaling

Inorganic fouling or scaling is the formation of mineral precipitates on the membrane surface. For a salt-rejecting membrane system such as is used for NF and RO, the concentration of the dissolved mineral salts can easily be concentrated 4–10 times depending on the operating conditions and membrane salt-rejection efficiency [29], thereby resulting in concentration polarization at the membrane surface. When the concentration of the salts exceeds their solubility limit, they can crystallize onto the membrane surface that leads to scale formation. The most common constituents of scale in RO applications are calcium carbonate, calcium sulphate, calcium phosphate, barium sulphate and silicate scale [12]. Research has been devoted to investigating the