Desalination xxx (2015) xxx–xxx

Contents lists available at ScienceDirect

Desalination

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

Online monitor for the reverse osmosis spiral wound module — Development of the canary cell

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HIGHLIGHTS

- High-pressure flat sheet cell capable of physically simulating a spiral wound module
- Application of a controllable system for an early warning monitor for RO fouling
- Non-invasive monitoring of high pressure colloidal fouling and cleaning
- A dimensionless correlation curve for the spiral wound module and the canary cell

ARTICLE INFO

Article history:
Received 15 October 2014
Received in revised form 8 April 2015
Accepted 12 April 2015
Available online xxxx

Keywords:
Colloidal silica
Reverse osmosis
Spiral wound module
Canary cell
Ultrasonic time-domain reflectometry (UTDR)

ABSTRACT

The development of a side-stream reverse osmosis cell, called the 'canary cell', to simulate the spiral wound module (SWM) is described. Representative fouling rates and ex-situ membrane autopsies show the capability of the canary cell to simulate the SWM under controlled hydrodynamics and flux conditions. The development of a dimensionless calibration curve allows the canary cell to act as an early warning system with respect to the SWM. The rate of cake thickness increase was also measured by ultrasonic time domain reflectometry coupled to the canary cell and used to monitor membrane fouling and cleaning.

1. Introduction

It is anticipated that the contribution to the global water supply from desalination and water reuse will continue to increase [1] with the leading technology being reverse osmosis (RO) [2–5]. It is likely that a significant reduction in the cost of desalination could emerge from process improvements that include, optimization of process configurations, process schemes and operation [6]. It is evident that energy consumption accounts for the majority of the operating costs in RO desalination [7–9]. However fouling frequently decreases productivity with either less flux at fixed pressure or increased pressure to maintain flux. Hence, significant savings could be made in the energy costs by pre-empting fouling problems in order to minimize the loss in productivity.

Once the RO process is in operation, there are two avenues to preempt fouling problems. First, the fouling propensity of the feed water can be measured and taken into consideration in the process operation. The available metric for assessing the fouling propensity is the Silt Density Index (SDI), which is entirely empirical and potentially unreliable [10–13]. The other approach is to monitor the 'state of the process' by detecting the presence of foulant on the membrane surface. This is difficult in practice for a spiral wound module due to its complex geometry. However it is more straight forward using a fouling monitor on a side-stream cell simulating the RO elements in the main plant. This could have benefits relative to the measurement of pressures and flows in the main plant that can fail to detect incipient fouling [14] since they are integral measurements over the whole system. Changes in pressures and flows tend to manifest only when fouling is well established. There is a need for better tools and measurements for an early warning system whereby detailed local observations of the membrane processes affected by fouling can be monitored in-situ, in real-time and non-destructively so that specific countermeasures can be taken [15,16]. This is the role of the side-stream cell.

The focus of this paper is to report on the development of a 'canary cell' that permits monitoring the fouling process in an RO membrane

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http://dx.doi.org/10.1016/j.desal.2015.04.014
0011-9164/

module via measurements on a side stream that employs non-invasive detection. The 'canary cell' is analogous to the canaries taken by miners in coal mines to warn of dangerous gases. The canary cell, in addition to being representative of a spiral wound RO module in terms of materials, spatial dimensions, and hydraulics, is characterized in terms of its accuracy and reproducibility under different conditions that can simulate the operating conditions at different locations in spiral wound module elements in a train. With the integration of sensors, such as non-invasive ultrasonic time domain reflectometry (UTDR), the canary cell has the capability to monitor fouling in-situ, in real-time and non-destructively.

This paper is organized as follows. Section 2 provides a brief overview of the state-of-the-art for both fouling monitors and UTDR. Section 3 summarizes the design and procedure for the experiments. The results are presented and discussed in Section 4. The conclusions are summarized in Section 5.

2. Prior studies

This section gives a brief review of prior studies concerning the development of fouling monitors. This is followed by a review of the fundamentals of the UTDR technique and the rationale for using UTDR.

2.1. Fouling monitors state-of-the-art

The 'canary cell' fouling monitor used in this study has been developed from the RO crossflow cell used by Chong et al. [17–19]. The Chong cell was designed to simulate the flow in a typical RO spiral wound module (SWM), and its key features are appropriate channel height, operation with or without flow channel spacers, and with controllable crossflow and flux. This cell design has been used to study RO fouling by colloids and biofilms [18,19,33,37], and coupled with noninvasive detection by UTDR [32,33,37], electrical impedance spectrometry [20] and the salt-pulse technique [18,19].

Similar fouling monitors have been described by others. The Membrane Fouling Simulator (MFS) described by Vrouwenvelder [21–25] has sensitive pressure transducers and is claimed to represent the SWM in terms of the development of flow channel pressure drop. It has also been coupled to magnetic resonance imaging (MRI) to study the development of biofouling. However in most studies it has not been operated with permeate flow. Hoek et al. [26,27] have described a high pressure membrane cell equipped with an external monitor using an optical microscope with reflected fluorescence imaging for detection of (bio)fouling development and cleaning. For scale fouling, Cohen et al. [28–30] have developed a pressurized cell coupled to a microscope and imaging system to detect and quantify crystal formation on the surface. Such fouling monitors can be useful tools and to provide realistic early warning information they need to be able to provide reliable simulation of the SWM. Therefore, the focus of this paper is to establish that the fouling phenomena (rate and nature) in the canary cell are similar to that in a commercial SWM operated at the same conditions.

2.2. Overview of UTDR

2.2.1. Fundamentals of UTDR

An ultrasonic wave provides information on the media through which it travels. Its velocity c is a property of the material through which the waveform travels. The distance between a reflecting interface and the transducer Δd, and the velocity c determine the time t for a waveform to travel through a medium, which is given by [31]

$$t = \frac{2\Delta d}{c}. \qquad (1)$$

The arrival time obtained from a plot of the instantaneous voltage of the UTDR waveform shown schematically in Fig. 1b provides information on the media being studied. A new peak F distinct from peak A, which emanates from the membrane/feed solution interface, will be generated if the foulant layer thickness is within the UTDR spatial resolution determined by the transducer frequency. If the spatial resolution, which is a function of the frequency and speed of sound wave through the media, is limiting, the fouling layer will not create a distinct peak but will cause the arrival time of peak A to decrease, shown in Fig. 1b as peak A′. Using any stationary reference point, e.g., reflection T or B in this case, the arrival times of peaks A and F (or A′) permit determining the height of the foulant layer or the membrane (at a filtration time for fouling = 0 min). The accuracy of UTDR measurements has been verified in prior work on both the thicknesses of inorganic silica foulant layer via scanning electron microscopy [32] and biofilms via confocal scanning laser microscopy [33].

2.2.2. Rationale for using UTDR

UTDR has been successfully used to study membrane processes for more than a decade. Measurement of thickness changes has been proven for various processes such as the evaporative casting of polymeric films [34], membrane compaction owing to high-pressure [35,36], and cake layer growth of various foulants [32,33,37–52]. Non-invasive measurement of membrane fouling and cleaning has also been done using UTDR [32,33,39,46–52,71,72]. Large scale applications have also been demonstrated by using UTDR to study commercial spiral wound RO modules [51,52]. Hence it is well established that UTDR has the potential to observe fouling in-situ, in real-time and non-destructively. Although ultrasonic reflectometry in the frequency domain has been demonstrated for the characterization of foulant growth, in particular biofilm growth on membrane coupons exposed in a bioreactor [53, 54], it requires the use of immersion transducers that are not designed for high pressure applications. Moreover, recent studies have shown that the capability to predict RO fouling is governed by the ability to model the phenomenon of cake-enhanced osmotic pressure and is dependent on the thickness of the foulant layer [37]. Therefore, the use of ultrasonic reflectometry in the time domain is preferred.

Non-invasive, in-situ, real-time observation of membrane processes can also be done via optical methods [17,22–24,26–30] due to its high sensitivity and the ability for visual observation. However, optical methods usually require a special membrane cell with a transparent window and are unable to study opaque or concentrated samples [33, 55]. They are also constrained by depth of field considerations and not well suited to measurement of foulant height; UTDR does not have these limitations. Hence, UTDR, as a non-optical method, is attractive because of its sub-micron resolution, ability to detect height changes, rapid response time, ease of implementation, and sensitivity [33].

3. Experiment design and procedures

3.1. Design considerations

3.1.1. Canary cell (fouling monitor)

The ideal fouling monitor has several requirements [17]. The monitor needs to: (1) be representative of the membrane element; (2) be accurate and reproducible; (3) allow the assessment of membrane performance; (4) allow the assessment of fouling in-situ, in real-time and non-destructively; (5) be user-friendly and (6) have low or reasonable costs. In summary, the fouling monitor needs to be representative of a RO spiral wound module element by having the same material in terms of membrane and spacers, the same spatial dimensions in terms of channel height and product spacer channels, and the same hydrodynamics and flux. In addition, the measurements from the fouling monitor need to allow the collection of a database that facilitates their interpretation under different hydrodynamic conditions representative of the spiral wound RO module and/or at different locations of an RO stage or train. Finally, the monitor needs to be able to detect the fouling

Please cite this article as: S.T.V. Sim, et al., Online monitor for the reverse osmosis spiral wound module — Development of the canary cell, Desalination (2015), http://dx.doi.org/10.1016/j.desal.2015.04.014