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Monitoring fouling behavior of reverse osmosis membranes using electrical impedance spectroscopy: A field trial study

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HIGHLIGHTS

- EISFM was used to monitor the performance of RO train in Singapore NEWater plant.
- Maximum in the normalised $Z_{\text{real-DP}}$ was observed well before CIPs were carried out.
- Mitigation measures could be initiated based on the occurrence of $Z_{\text{real-DP}}$ peaks.
- The frequency of CIPs could be reduced by implementing physical control measures.
- The nature of fouling layer could be identified from the trend of $Z_{\text{real-DP}}$.

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ABSTRACT

An electrical impedance spectroscopy fouling monitor (EISFM) was used to monitor the performance of a reverse osmosis (RO) treatment train in a NEWater plant in Singapore. A 'canary cell' equipped with an EIS measurement system was installed in a side stream of the train. It was operated at the same hydrodynamics as the train to simulate the fouling conditions in the spiral wound modules. The correlation between the EISFM response and plant performance was investigated. When trending the real part of the impedance of the low frequency signal element ($Z_{\text{real-DP}}$) over time, there was a maximum in the normalised $Z_{\text{real-DP}}$ observed well before chemical cleaning which was indicated by the traditional operational criteria. The occurrence of $Z_{\text{real-DP}}$ peaks can be used as an indicator to initiate mitigation measures, such as adjustment of flux or crossflow velocity. As such, the frequency of chemical CIPs could be reduced. Furthermore, by observing the trend of $Z_{\text{real-DP}}$ over time, it was possible to identify the nature of the fouling such as the build-up of a layer of inorganic colloids. This was validated by membrane autopsy studies. This study confirms that the EISFM is suitable for monitoring the performance of RO in a real plant.

1. Introduction

In most reverse osmosis (RO) water treatment plants, membrane fouling problems are generally monitored through changes in (1) pressure drop (ΔP) along the channel, (2) transmembrane pressure (TMP) and (3) salt rejection. However, these parameters represent the averaged values over the whole system and therefore provide little information on incipient fouling that can be initially a localized phenomenon. As a result, plant operators can only rely on arbitrary values of these parameters to initiate a chemical clean-in-place (CIP) cycle. As a rule of thumb, CIP is conducted when a 15% increase in ΔP or TMP or 15% drop in salt rejection is observed. However, when such observations are made, the membrane may already be significantly fouled. This may lead to more frequent or more difficult chemical cleaning events to restore the membrane performance, especially during the latter part of the lifespan of the membrane. Therefore, there is a pressing need to have sensitive tools to monitor the membrane fouling process so that specific countermeasures can be taken *before* significant fouling is observed. Countermeasures such as physical cleaning could be carried out instead of CIP to control fouling so as to reduce the number of CIP events and to minimize cost incurred in chemical usage.

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One way to provide such sensitive observation of the spiral wound RO elements in the plant is to install appropriate sensors on a side-stream cell [1]. The role of this side-stream cell (also known as a "canary cell") is to mimic the fouling conditions in the RO elements, where the sensors integrated into the cell provide information on the incipient fouling. Sim et al. (2015) have successfully shown the capability of the canary cell to simulate the spiral wound module under similar hydrodynamic conditions. The canary cell must consist of same membrane and spacers materials and most importantly, having similar hydrodynamics conditions [1].

There are several non-invasive monitoring techniques reported in the literature. For example, Vrouwenvelder et al. [2,3] developed a Membrane Fouling Simulator (MFS) to monitor biofouling in RO and NF filtration of surface water. This technique is based on monitoring the increase in ΔP through the MFS device without the presence of permeation flux. The results only provide partial information on the fouling problem specific to spacer fouling, rather than membrane fouling. Uchymiak et al. developed a novel RO ex-situ scale observation detector (EXSOD) to visually monitor scale formation on a membrane surface [4]. The EXSOD consists of a small high pressure RO cell, with its membrane surface digitally imaged in real-time. This device can detect mineral salt scaling at the very early stages of formation, well before any measurable increase in pressure. Other imaging-based techniques include microscopy imaging using a high pressure optical membrane module [5,6], an optical coherence tomography method to detect fouling [7] and Earth's field (EF) Nuclear Magnetic Resonance (NMR) to provide early detection of biofouling of a spiral wound RO element [8].

In addition, techniques such as ultrasonic time-domain reflectometry [1,9–15], salt pulse tracer method [16–18] and electrical impedance spectroscopy (EIS) [19–21] have been reported to be capable of monitoring fouling in-situ, in real-time and non-destructively. In particular, EIS has been demonstrated in several RO fouling studies to be a promising monitoring tool [19–24] and capable of characterizing the nature of the fouling [21,22,25]. However, this technique has not yet been tested in an actual water treatment plant.

In this study, an electrical impedance spectroscopy fouling monitor (EISFM) was integrated into a canary cell to monitor the fouling behavior of a bank or train of RO modules in a water reclamation plant in Singapore. A key objective in this study was to identify which EIS signal parameter best correlated with reported plant performance data and CIP events. Importantly, we wanted to evaluate if the EIS signal could provide early indications of performance changes due to incipient fouling. As such, this study focused only on monitoring the changes of EIS parameter over time as there was no provision to exercise control over when a CIP was to be performed. At the end of the study, based on tracking the operation at the plant, we proposed several criteria that could be used to initiate fouling mitigation measures based on EIS parameter. Furthermore, a membrane autopsy was also performed to confirm fouling mechanisms suggested by the EISFM.

2. Materials and method

2.1. Installation of EISFM in a NEWater plant

An EISFM was installed at a NEWater plant to monitor the performance of one of the RO trains in the plant. The feed to the RO is secondary treated municipal wastewater that has been pretreated by MF with a nominal pore size of 0.1 μm. The RO trains consist of two stages, operating at an overall recovery of 75%. In this study, the EISFM canary cell was located on side stream of stage 1 of the RO system. The layout of the RO process and the side stream EISFM canary cell is shown in Fig. 1.

As the EISFM canary cell was installed on side stream of RO stage 1, it was subjected to a similar pressure as RO stage 1. In order to mimic the fouling conditions in the RO spiral wound module element, the canary cell had similar membrane and spacers as well as the same hydrodynamics and flux [1]. The flow to the canary cell was regulated by a flow control valve and was maintained at a similar Reynold number as RO stage 1 and at the same production flux using mass flow controller (Brooks Instrument, Model 5882), located in the permeate stream. The membrane used in this study was RO flat sheet membrane (Hydranautics Nitto Group Company, ESPA 2). Furthermore, in the set-up as shown in Fig. 1, the canary cell would undergo the same cleaning regime as the main RO train.

The operational permeate flux of the canary cell was set at 17.6 Lm^{-2} h^{-1} and its crossflow velocity was maintained at 0.18 ms^{-1}, equivalent to $Re = 184$ (the method to obtain Reynolds number of a spacer-filled channel is described by Schock and Miquel [26]). A data acquisition system (National Instrument, Model PCI 6014 and Labview software) was used to record the pressure and flux readings. It should be noted that the membrane coupon in the EISFM cell was new but the RO trains in the NEWater plant had been operated for several years. Therefore, it was assumed that the values of parameters deduced from the impedance measurement provide relative trends rather than absolute values directly equivalent to those for the membranes in the plant.

2.2. Description of EISFM cell

The dimensions of the EISFM cell were 210 mm × 6 mm × 0.73 mm and the effective membrane area was 0.0126 m^2. Detailed description of the four-terminal crossflow EIS chamber has been given in our previous studies [21,22,24,25]. Briefly, the cell was equipped with two pairs of electrodes for current injection and the measurement of voltage across the membrane. The electrodes were mounted on top and bottom of the

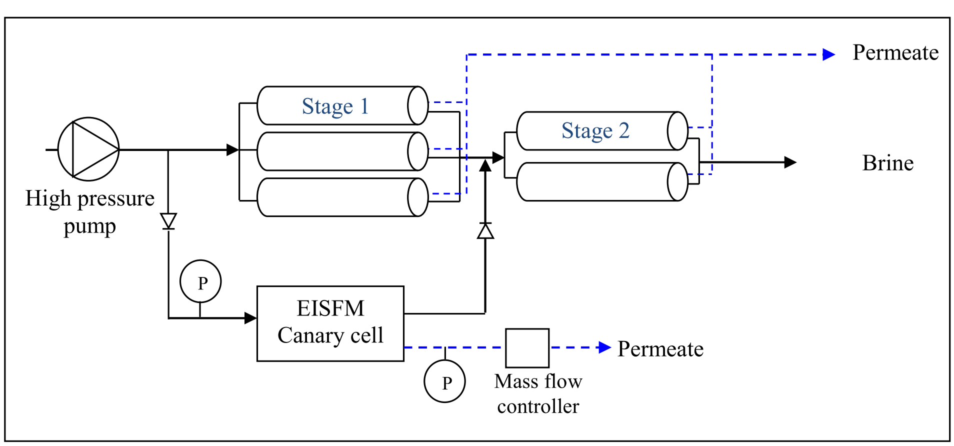

Fig. 1. Layout of the RO process in a NEWater plant and the location of the EISFM canary cell. Note that the schematic is not drawn to scale.