Desalination 443 (2018) 143–164

Contents lists available at ScienceDirect

Desalination

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

The use of ultrasound to mitigate membrane fouling in desalination and water treatment

M. Qasim[a], N.N. Darwish[a], S. Mhiyo[b], N.A. Darwish[a,*], N. Hilal[c]

[a] Department of Chemical Engineering, American University of Sharjah, P.O. Box 26666, Sharjah, United Arab Emirates
[b] Faculty of Chemical and Petroleum Engineering, Al Baath University, Homs, PO Box 77, Syria
[c] Centre for Water Advanced Technologies and Environmental Research (CWATER), College of Engineering, Swansea University, Fabian Way, Swansea SA1 8EN, UK

ARTICLE INFO

Keywords:
Membrane fouling
Membrane cleaning
Flux enhancement
Ultrasound
Pretreatment

ABSTRACT

Fouling is recognized as a serious challenge in reverse osmosis desalination and in different membrane-based separation technologies. Membrane fouling not only reduces the permeate flux and the membrane productivity but also significantly decreases the membrane lifespan, increases the energy and feed pressure requirement, and increases membrane maintenance and replacement costs. As a result, the consequences of membrane fouling have always stimulated research investigations into different fouling mitigation strategies. In this context, application of ultrasound is an effective technique that can be used as an external aid for both membrane fouling control and membrane cleaning. The purpose of this review paper is to provide an updated and comprehensive review of ultrasound as an effective tool for membrane flux enhancement and membrane cleaning. In addition to briefly discussing the mechanisms of membrane fouling, theories related to ultrasonic waves, acoustic cavitation, cavitational collapse, and ultrasound-induced effects are addressed. The key challenges in industrial application of ultrasound for flux enhancement and membrane cleaning are also discussed.

1. Introduction

Membranes are of immense importance in industrial separation processes and are extensively used in a wide range of applications including desalination [1–6], wastewater treatment [7–12], food and beverage processing [13–17], biotechnology [18–20], and petrochemical processing [21,22]. Membrane-based separation processes are typically characterized by advantages such as selective separation, low space requirement, process and plant compactness, low chemical requirement, operational simplicity, and ease of process automation [23,24]. Despite these advantages, permeate flux decline is one of the main limitations in membrane-based technologies. The flux decline is mainly attributed to the concentration polarization and membrane fouling phenomena [25]. Concentration polarization occurs due to solute build-up in the mass transfer boundary layer near the membrane rejection surface and results in decreased effective transmembrane pressure (TMP) owing to the generation of osmotic back pressure [26,27]. On the other hand, membrane fouling is a complex phenomenon that involves deposition of materials on the membrane surface or within the membrane pores [28]. While concentration polarization is essentially reversible [29], membrane fouling presents a greater challenge and contributes significantly to the decline in flux, productivity, and membrane lifespan, increase in the energy consumption due to high feed pressure requirement, and increase in the membrane maintenance, cleaning, and replacement costs [23]. Therefore, research investigations into fouling control and membrane cleaning methods are of considerable importance.

Fouling control methods aim to decrease the likelihood of membrane fouling. Often pretreatment methods are used as preventative measures for controlling membrane fouling. These include the use of prefilters, screens, precipitation, coagulation, flocculation, or chemicals to reduce the amount of foulants in the feed [30–33]. In addition, membrane surface modification may be performed to lower the affinity of foulants for the membrane surface [30,34–39]. Membrane fouling can also be controlled by optimizing the operating conditions such as pH, temperature, pressure, and hydrodynamics [30,34]. Other methods to control membrane fouling rely on enhancing the shear on the membrane surface. These methods include gas bubbling, rotating disks/rotors, rotating membranes, and vibratory systems [30,40,41]. Despite being effective, scale-up and equipment cost are major challenges in industrialization of the shear-enhanced fouling control methods [41].

Membrane cleaning methods are typically used when fouling control methods fail and the membrane must be cleaned for full or partial removal of the foulants. Cleaning methods may be classified into

* Corresponding author.
E-mail address: ndarwish@aus.edu (N.A. Darwish).

https://doi.org/10.1016/j.desal.2018.04.007
Received 6 February 2018; Received in revised form 11 April 2018; Accepted 13 April 2018
0011-9164/

chemical or physical methods. Chemical cleaning methods involve application of chemical agents such as caustic soda, oxidants, acids, chelates, or proprietary surfactants in order to weaken cohesion forces between the foulants and the membrane surface [42]. These methods usually require large amount of chemicals, pose safety concerns, cause damage to the membrane, and generate waste streams that result in secondary pollution [30]. Physical cleaning methods, on the other hand, involve application of hydraulic or mechanical cleaning forces in order to loosen and detach the foulants [43]. This may include cleaning the membrane using a hose pipe, sponge, or brush that requires significant physical effort [27]. Backwash has proved to be an effective physical cleaning method. However, it is only applicable to tubular and hollow fiber membranes due to high pressure durability requirement [30,44]. In addition, hydraulic flushing (forward and reverse) can be used that involves removal of surface deposits using a rinsing solution. However, flushing method is typically employed after the foulants have been loosened by other cleaning method such as chemical cleaning and backwash [43]. Also, both flushing and backwash require periodic process shutdown.

Ultrasound application provides an alternative technique for membrane fouling control and membrane cleaning in desalination and water treatment. Although there are numerous experimental studies on the use of ultrasound in different membrane-based technologies, only few technical reviews exist in the literature [27,30,45]. This review paper outlines the theory and mechanisms of membrane fouling and ultrasound irradiation and aims to provide an updated and comprehensive review of ultrasound-assisted membrane fouling mitigation. The key challenges related to ultrasound application in membrane processes are also discussed.

2. Theory and mechanisms of membrane fouling

Membrane fouling is a challenge in both pressure-driven membrane processes such as microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO) and osmotically-driven membrane processes such as forward osmosis (FO) and pressure-retarded osmosis (PRO). Fouling is also inevitable in other membrane-based processes including membrane bioreactor (MBR) and membrane distillation (MD). An understanding of membrane fouling fundamentals and the involved mechanisms is crucial to the development of novel approaches for fouling control and membrane cleaning. Therefore, this section outlines the fundamental concepts in membrane fouling.

Membrane fouling is a complex phenomenon that involves physical and chemical interactions between the different foulants present in the feed and between the foulants and the membrane surface. The overall effect of fouling is to decrease the active membrane area or increase the resistance across the membrane leading to a decreased flux for a given TMP. In general, membrane fouling may occur in the form of adsorption, pore blockage, particle deposition, or gel formation [28]. Adsorption refers to specific interactions between the foulants and the membrane surface or the membrane pore walls that result in an increased hydraulic resistance. Pore blockage, on the other hand, involves plugging of the membrane pores that results in a decreased flux across the membrane. Deposition of foulants simply refers to the layer by layer accumulation of foulants on the membrane surface that offers an additional hydraulic resistance known as cake resistance. In case of fouling due to gel formation, cross-linked three-dimensional networks of deposited particles, such as macromolecules and colloidal substances, are formed on the membrane surface. The gel layers lack of connectivity between the pores and, therefore, present high resistance for mass transport across the membrane [46]. Accumulation of foulants on the surface is often termed as external fouling while fouling within the membrane pores is also known as internal fouling.

The typical flux-time curve depicted in Fig. 1 [47] highlights the serious consequences of membrane fouling in UF and MF processes. Typically, the flux decline occurs in three stages. In stage I, there is a

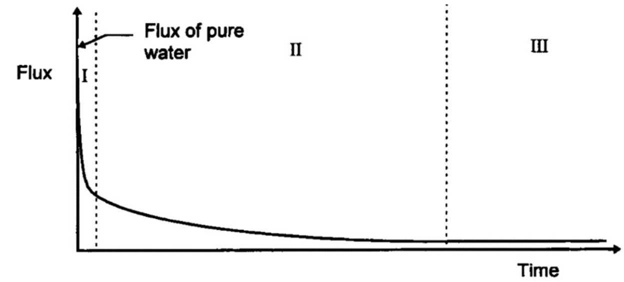

Fig. 1. The three stages of flux decline due to membrane fouling. Stage I: quick initial decline, stage II: long-term steady decline in flux, stage III: time-independent steady-state flux.
(Adopted from [47].)

quick flux decline due to rapid pore blocking at the start-up of the process. In stage II, the flux further declines which is attributed to the formation and growth of the cake layer. The flux continues to decline in this stage as the cake layer grows and becomes thicker. In stage III, the process reaches steady-state and the cake grows to its equilibrium thickness [47]. The difference between the initial pure water flux and the steady-state flux can be very large. For instance, in UF and MF, the steady-state flux obtained is usually < 5% of the pure water flux [28].

Different types of foulants may be encountered in membrane-based separation processes depending on the characteristics of the feed water. Generally, the foulants are classified into the following four types [23]:

- Organic foulants: These consist of dissolved or colloidal organic matters that are deposited/adsorbed on the membrane and include humic acid, fulvic acid, peptides, proteins, polysaccharides, and many others
- Inorganic foulants: These include dissolved or sparingly soluble inorganic components that precipitate due to pH changes or due to oxidation. Examples include calcium sulfate, calcium carbonate, silica, iron, manganese, etc.
- Particulates/colloids: These include organic and inorganic particles or colloids that accumulate on the membrane surface, block the pores, or form cake layer, for example, suspended solids, silt, and clay
- Microbiological organisms: These cause biofouling by adhesion and growth of bacterial and fungal species and excretion of extracellular materials

Membrane fouling is affected by a number of factors such as material, type, pore size distribution, and surface characteristics of the membrane, feed solution chemistry, and hydrodynamics of the membrane process [28].

2.1. Organic fouling

Organic fouling is typical in membrane-based separation processes due to the ubiquitous presence of dissolved organic matter (DOM) in surface water, wastewater, and sewage. DOM can be categorized into: (1) natural organic matter (NOM) that are produced through metabolic reactions in drinking water sources, (2) synthetic organic compounds (SOC) that are discharged into wastewater streams from household and industries, and (3) soluble microbial products (SMP) that are formed during biological water treatment [23]. In case of NOM, the major constituents in surface or ground waters are humic substances (humic acids, fulvic acids, and humin) formed by decomposition of plant and animal residues [48]. Humic substances contain both aromatic and aliphatic components of carboxylic and phenolic functional groups. Also, NOM constitutes non-humic fractions that are composed of transphilic acids, amino acids, proteins, and carbohydrates [49]. NOM can cause organic fouling in several ways. It can deposit or adsorb