



A mini-review on membrane fouling

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HIGHLIGHTS

- ▶ The cause, fouling phenomena and fouling mechanisms of membrane fouling are reviewed.
- ▶ Better understanding of fouling in membrane applications is provided.
- ▶ The predominant foulants in various membrane applications are reviewed.
- ▶ Different fouling mechanisms can provide a really complex matrix.

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ABSTRACT

During the last decades, the interest of using membrane technology has emerged in wastewater treatment as well as drinking water and process water production. However, the impediment of the membrane technology is the fouling problem and consequently higher operating and membrane replacement cost. Hence, better understanding of membrane fouling is not only the key to solve the problems, but also is one of the main factors driving membrane technology forward. This mini-review paper identifies the major foulants and the principal membrane fouling mechanisms such as pore blocking, cake formation, concentration polarization, organic adsorption, inorganic precipitation and biological fouling. It also gives a holistic review about different fouling phenomena during the application of membrane separation technologies in water and wastewater treatment, with specific references to various problems, membranes, treatment processes and its practical applications.

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1. Introduction

Membrane based separations have gained increasing popularity over the last three decades and become one of the most promising technologies for the 21st century. As an advanced wastewater treatment technology, membrane technology has been playing a key role in lower pollutant levels in purifying and/or concentrating a wide variety of fluids from water and wastewater to pharmaceutical and chemical products. Membrane processes are of great interest because they reduce the number of unit operations, recycle process water, and recover valuable products for other applications. They have also been considered as attractive alternatives compared to conventional wastewater treatment processes due to their inherent advantages such as selective separation, continuous and automatic operation, easy and well-arranged process conduction, purification without the addition of chemicals, easy scale-up and low space requirement (Sonune and Ghate, 2004). Therefore, membrane techniques (e.g. microfiltration (MF), ultrafil-

tration (UF), nanofiltration (NF) and reverse osmosis (RO)) in general and membrane bioreactors (MBRs) in particular have been widely applied to for advanced water and wastewater treatment.

However, as various factors govern the operating cost of a membrane system, such as power requirements, costs of power, labor, materials, membrane cleaning, scale inhibition and membrane life and replacement, some limitations remain in using membranes for water and wastewater treatment (Bennett, 2005). The major obstacle for the application of membrane processes is the rapid decline of the permeate flux over time as a result of membrane fouling. That is to say, membrane efficiency and membrane fouling present the significant challenges for RO, NF, UF and MF related technologies (Frost and Sullivan et al., 2007). Hence, the aims of this paper are to address the major issues on fouling in various membrane applications, as well as offer a comprehensive overview about different foulants and fouling mechanisms.

2. Membrane foulants, fouling type and mechanisms

Membrane systems can be operated in either constant permeate flux (flow rate per unit membrane area, $L/m^2 h$) with variable

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transmembrane pressure (TMP) or constant TMP with variable permeate flux. The former mode is the common one. Based on the operating TMP, membranes for water treatment and reuse can be broadly categorized as low pressure membranes (LPMs) and high pressure membranes (HPMs). LPMs include microfiltration (MF) and loose ultrafiltration (UF) membranes, which are operated at relatively low TMPs, typically less than 100–200 kPa. On the other hand, HPMs such as tight UF, nanofiltration (NF) and reverse osmosis (RO) membranes are operated at relatively high TMPs (>200 kPa).

Membrane fouling occurs during an increase in TMP to maintain a particular flux or during a decrease in flux when the system is operated at constant pressure. Membrane fouling can be classified as reversible fouling and irreversible fouling, of which the distinction is entirely dependent on the context in which membranes are operated and cleaned. Reversible fouling (including backwashable and non-backwashable) occurs due to the cake layer or concentration polarization of materials at the membrane rejection surface. Membrane with backwashable reversible fouling can be restored through appropriate physical washing protocol such as backwashing or hydrodynamic scouring (surface washing), while the non-backwashable reversible fouling only can be removed by chemical cleaning. Irreversible fouling occurs by chemisorption and pore plugging mechanisms. In case of irreversible fouling, the loss in transmembrane flux cannot be recuperated hydrodynamically or chemically. This means that the membranes must go through extensive chemical cleaning or be replaced.

Fouling of membranes is caused by complex physical and chemical interactions between the various fouling constituents in the feed and between these constituents and the membrane surface. Mass transport can lead to the attachment, accumulation, or adsorption of materials onto membrane surfaces and/or within membrane pores. Previous studies have demonstrated that membrane fouling and the characteristics of foulants are determined by feed water composition, the concentration of the major constituents, water chemistry (pH, ionic strength, and divalent cation concentration), membrane properties (surface morphology, hydrophobicity, charge and molecular weight cut-off), temperature, mode of operation and hydrodynamic conditions (initial permeate flux and crossflow velocity) (Li and Elimelech, 2004). Hence, any factors that could change the hydrodynamic characteristics of membrane modules and the chemical characteristics of feed waters would affect the overall membrane performance (Zhou and Smith, 2002). Consequently, the combined physical and chemical effects will control the degree of attachment, as well as will determine how severe the fouling is and what strategies will be effective in controlling it (Pearce, 2007). Normally, foulants can be classified into the following four categories:

- Particulates: inorganic or organic particles/colloids act as foulants which can physically blind the membrane surface and block the pores, or hinder transport to the surface by the development of a cake layer;
- Organic: dissolved components and colloids (e.g. humic and fulvic acids, hydrophilic and hydrophobic materials and proteins) which would attach to the membrane by adsorption;
- Inorganic: dissolved components (e.g. iron, manganese and silica) which tend to precipitate onto the membrane surface due to pH change (scaling) or due to oxidation (e.g. iron or manganese oxides). Coagulant/flocculant residuals may also be present as inorganic foulants; and
- Micro-biological organisms: the microbiological category covers vegetative matter such as algae, and microorganisms such as bacteria which can adhere to the membranes and cause bio-fouling (biofilm formation).

Raw waters contain a wide distribution of fine particles, dissolved organic compounds, colloids, less soluble salts and biological growth that can cause membrane fouling. Fouling by different foulants can be considered to occur by different mechanisms. Recent research has identified six principal fouling mechanisms: (i) pore blocking, (ii) cake formation, (iii) concentration polarization, (iv) organic adsorption, (v) inorganic precipitation, and (vi) biological fouling.

3. Particulate/colloidal fouling

Particulate matter in natural waters and wastewaters has been classified by Rudolfs and Balmat (1952) in the following categories:

- Settleable solids > 100 μm
- Supra-Colloidal solids 1 μm to 100 μm
- Colloidal solids 0.001 μm (10 \AA) to 1 μm
- Dissolved solids < 10 \AA

Colloids cover a wide size range, from a few nanometers to a few micrometers. Aquatic colloids comprise corrosion products, silt and clay, precipitated crystals, colloidal silica and sulfur, precipitated iron and aluminum compounds from incomplete treatment. Some high molecular weight (MW) organic substances (e.g. polysaccharide, peptidoglycans, proteins and humic aggregates) and their clusters (e.g. cellular debris) are also characterized (to a certain degree) as colloidal foulants since many features of their behavior are common with those of inorganic colloidal particles (Yiantsios and Karabelas, 1998). Generally, membrane fouling by particulates/colloids is attributed to initial pore blocking followed by cake formation (Lim and Bai, 2003).

Colloids close to the size of membrane pores can cause pore blocking while those much larger than membrane pores can lead to cake formation that is more easily removed (Huang et al., 2008). Convection, Brownian diffusion, shear-induced diffusion, inertial lift, gravitational settling and lateral migration are the main transport mechanisms of colloids and fine particles from the bulk of the flowing suspension to the membrane surface, which strongly depend on shear rate, particle size and the bulk concentration of particles in the feed solution (Belfort et al., 1994). The mechanisms of particulate/colloidal fouling include pore blocking, cake formation and concentration polarization (Kennedy et al., 2003). Pore blocking is the initial phase of particulate fouling as well as the most severe mode of fouling, which can be described as three different types:

- (1) Standard pore blocking: the constriction of the pore opening due to deposition of particles around the pore entry;
- (2) Complete pore blocking (pore sealing): the plugging of a pore; and
- (3) Intermediate pore blocking: a combination of the previous two as the build up of deposited particles begins to bridge the pre openings.

As additional particles continue to deposit on the initial layer, a cake layer will be developed in the next stage. As soon as the cake forms, the cake layer will control transport and removal, and effectively takes over the role of the membrane. Cake permeability can be affected by particle shape and size, particle deformability and operating parameters such as TMP (Pearce, 2007). It was observed that the rate of flux decay increased with increasing TMP, which could be caused by the thickness and the compactness of the cake layer. At high TMP, more particles accumulated on membrane surface and there was a high drag force resulting in cake compression. In addition, the cake layer on the membrane surface has been found to be microstructure, including its surface and cross-section, which consists of numerous irregular pores of different size

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