Journal of Membrane Science 454 (2014) 82–96

Contents lists available at ScienceDirect

Journal of Membrane Science

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

The role of cell-surface interactions in bacterial initial adhesion and consequent biofilm formation on nanofiltration/reverse osmosis membranes

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ARTICLE INFO

Article history:
Received 15 April 2013
Received in revised form
19 November 2013
Accepted 23 November 2013
Available online 10 December 2013

Keywords:
Bacterial adhesion
Membranes
Nanofiltration
Reverse osmosis
Biofouling
Fouling

ABSTRACT

Until recently, the realization that membrane biofouling during nanofiltration (NF) and reverse osmosis (RO) processes is an unavoidable occurrence, has led to a paradigm shift in which biofouling management approaches rather than biofouling prevention are now being considered. To implement this new concept, it is crucial to understand the fundamentals of cell-surface interactions during bacterial adhesion, a prerequisite to biofouling of membranes. As such, with membrane biofouling already being widely studied and documented, greater attention should be given to the factors involved in the initial bioadhesion onto membranes during NF/RO processes. This review focuses on the interactions between bacterial cells and NF/RO membranes, emphasizing the mechanisms of bacterial adhesion to NF/RO membranes with particular reference to the effects of micro-environmental conditions experienced at the membrane interface, such as feed-water composition, hydrodynamics, permeate flux and conditioning layers. This review also discusses membrane surface properties and how it relates to bacterial adhesion as well as latest advancements in antibacterial membranes, identifying areas that need further investigation.

Contents

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http://dx.doi.org/10.1016/j.memsci.2013.11.043

1. Introduction

Biofouling remains a major operating problem in nanofiltration (NF) and reverse osmosis (RO) plants and is a topic that has been extensively documented in the literature[1–6]. Biofilms are at the core of the problem and their recalcitrance leads to performance loss and the use of significant quantities of cleaning chemicals. In extreme cases the biofouling problem may reduce the operating life of the membrane module. Scientific studies in the context of NF/RO operations have predominantly focused on the mature biofilm and to a lesser extent on initial phase of bacterial adhesion. Initial colonization of a surface is the first step in biofilm formation [7]. This transition from a planktonic to a sessile lifestyle is often in response to a variety of environmental cues such as osmolarity, pH, carbon, iron availability, oxygen tension, and temperature [8].

The first step in adhesion is the immediate attachment of bacteria to a surface which is a reversible non-specific process. It is generally accepted that initial bacterial adhesion is a key part of the biofilm development process. However there is an increasing body of evidence suggesting that the rate of bacterial adhesion is not predictive of the extent of biofilm formation [9]. Experimental studies where both initial adhesion rate and biofilm formation rate were measured under comparable conditions are rarely found in the literature, showing a need for further investigation of the relationship between initial adhesion and biofilm formation. From the few studies that exist, it is generally accepted that there is no direct correlation between the levels of initial adhesion and the amount of biofilm formed [10–12]. A low adhesion rate might delay biofilm formation, but not prevent it [13]. This conclusion has important implications for the critical analysis of studies where biofouling resistance is claimed based on experimental data where only initial bacterial adhesion tests were undertaken.

Bacterial adhesion in membrane systems is a complex process that is affected by many factors including the environmental milieu, the characteristics of a conditioning film, bacterial properties and the material surface physical/chemical characteristics. Notwithstanding the poor relationship between initial adhesion rate and extent of subsequent biofouling, it is important to review the fundamentals of bacterial-membrane interactions, not least because of the possible important role of initial adhesion in the biofilm developmental process, but also to elucidate the role of these interactions in biofouling control strategies. The role of bacterial-membrane–solute interactions in composite fouling whereby biofilm formation occurs in tandem with other fouling processes such as organic fouling, scaling, etc. is particularly poorly understood. Some of the complexities of the environment in which biofilms are initiated on NF/RO membranes are shown schematically in Fig. 1.

The purpose of this article is to provide a comprehensive review of the mechanisms of bacterial adhesion to NF/RO membranes with particular reference to the effects of micro-environmental conditions experienced at the membrane interface. Key concepts relevant to NF/RO membrane operations including feed-water composition, hydrodynamics, permeate flux and conditioning layers are all discussed in the context of bacterial-surface interactions with cognizance of the current understanding of bacterial adhesion and biofilm formation.

2. Bacterial adhesion: general patterns

Mechanisms by which bacteria are transported to a surface can include Brownian motion, sedimentation due to differences in specific gravity between the bacteria and the bulk liquid, or convective mass transport, by which cells are physically transported towards the surface by the movement of the bulk fluid. When bacteria approach a surface they must overcome an energy barrier to establish direct contact with the surface. The repulsive or attractive forces consist of Lifshifz–van der Waals attractive forces, electrostatic

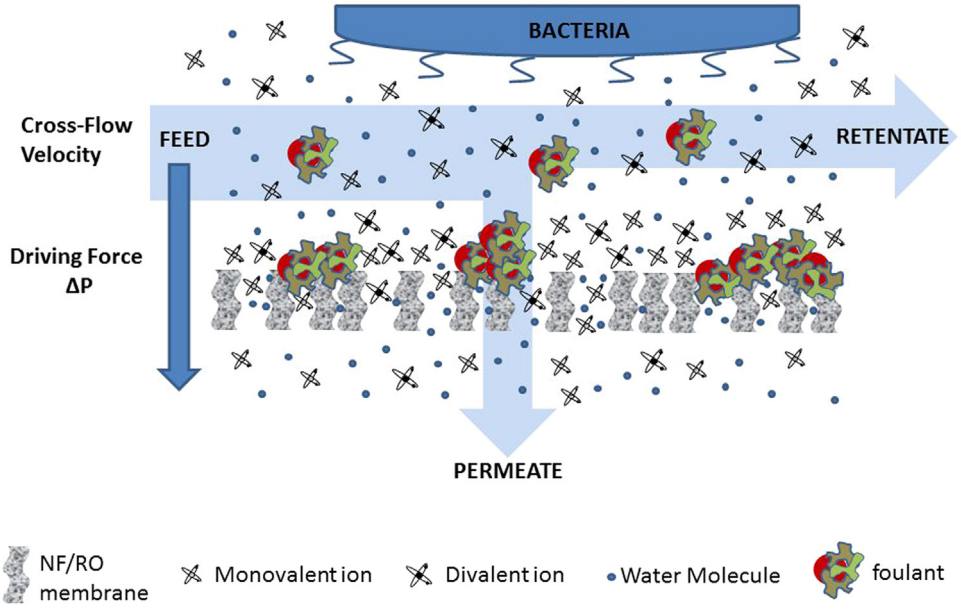

Fig. 1. Schematic outline of nanofiltration and reverse osmosis process operation, including fouling components and salts, the direction of cross-flow and permeate flow, the concentration polarization effect and the presence of microbes.