Separation and Purification Technology 207 (2018) 498–505

Contents lists available at ScienceDirect

Separation and Purification Technology

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

Analysis of surrogate bacterial cell transport to nanofiltration membranes: Effect of salt concentration and hydrodynamics

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ABSTRACT

Biofouling is a significant operational impediment in pressure-driven membrane processes. The early stage of biofouling involves bacterial adhesion at the membrane-liquid interface where the physical and chemical conditions are very complex. This study employed a sophisticated model of bacterial adhesion and was combined with a computational fluid dynamics (CFD) model to investigate the role of concentration polarisation and hydrodynamics on adhesion processes in membrane fouling simulators (MFS). The CFD model calculated the mass transfer phenomena in the membrane channel incorporating the concentration polarization effect using an algorithm that improves on previous research. The model was validated experimentally using a cross-flow system, under well-defined conditions with polystyrene microbeads as surrogate bacterial cells. The model was effective in predicting the microbead deposition pattern and explaining the decline of permeate flux along the channel and the microbeads deposition pattern.

1. Introduction

It is well established that biofouling is a primary cause of performance deterioration during Reverse Osmosis (RO) and Nanofiltration processes [1,2], typically manifested as hydraulic resistance which decreases permeate flux and can also impact on salt rejection [3–6]. The biofouling phenomenon during membrane separation processes is commonly initiated by bacterial deposition, which subsequently develops into a confluent biofilm matrix containing polysaccharides, lipids, dead and living cells [7]. The fouling layer on Reverse osmosis/Nanofiltration membrane influences the passage of solutes through the membrane [8]. While several factors, such as membrane surface charge, membrane roughness and the presence of conditioning layers have all been shown to affect the initial cell adhesion on membranes [9], permeate flux is recognized as the dominant force in the rate of bacterial deposition on membranes, as demonstrated experimentally [10] and through mathematical modeling [11].

Despite these findings, a comprehensive understanding of the hydrodynamics and mass transfer at the surface of nanofiltration membranes and how it impacts on bacterial adhesion remains unclear. Such knowledge would provide a fundamental understating in order to develop strategies for biofouling minimization with reference to permeate flux, hydrodynamics and membrane characteristics [12]. Previous studies have applied modelling tools for predicting specific hydrodynamics within cross-flow membrane systems. In one of the earliest reported studies of its type, Geraldes et al. simulated the mass transfer and hydrodynamics in 2-dimensional channels to predict the membrane permeation flux [13]. The simulation was further used to explore the effects of hydrodynamics on mass transfer of concentration boundary layer, which concluded that flow regimes, more specifically the decrease of Reynolds number were responsible for the increased mass transfer resistance [14]. Wiley and Fletcher were the first to use computational fluid dynamics (CFD) to model the flow and concentration polarization in both feed and permeate channels [15]. The properties of the fluid adjacent to the surface of the membrane were integrated into the hydrodynamic model to reveal concentration polarization. In 2005, Ahmad et al. studied mass transfer in the membrane channel based on the constant flux assumption [16]. Ahmad and Lau further incorporated the changing permeate flux in the boundary conditions and developed a more sophisticated model to describe the process [17]. So far, to the best of our knowledge, there are no reported studies investigating the possibility of predicting bacterial adhesion at the membrane interface, based on observed decreases in permeate flux along the filtration channel length. Therefore, there are two main objectives in this paper. Firstly, the mass transfer and permeate flux in membrane fouling simulators was simulated by developing a CFD model that combines film

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https://doi.org/10.1016/j.seppur.2018.06.072
Received 3 March 2018; Received in revised form 15 June 2018; Accepted 28 June 2018
Available online 30 June 2018
1383-5866/

Nomenclature

c_A	concentration (kg/m^3)
$\bar{c}$	average concentration (kg/m^3)
D_{AB}	binary mass diffusion coefficient (m^2/s)
h	membrane fouling simulator channel height (m)
l	membrane fouling simulator channel length (m)
J_v	permeate flux (m/s)
J_w	pure water flux (m/s)
L_p	hydraulic permeability (m/(Pa·s))
m_A	solute mass fraction ((kg of solute)/(kg of solution))
N_s	solute flux (kg/m^2·s)
P_s	overall solute permeability (m/(Pa·s))
R	true rejection
R′	1-R
Re	feed Reynolds number = $\rho u_f h/\mu$
Sc	Schmidt number = $\mu/\rho D_{AB}$
u	velocity in x – direction (m/s)
v	velocity in y – direction (m/s)
w	channel width (m)
x	x-coordinate (m)
y	y-coordinate (m)

Greek letters

σ	reflection coefficient
Γ	concentration polarization factor = $(m_{Aw}-m_{Af})/m_{Af}$
ρ	density (kg/m^3)
μ	viscosity (kg/m·s)
ΔP	transmembrane pressure (Pa)
δ_c	concentration polorization layer thickness (m)
ω	solute permeability (kg/N·s)
π	osmotic pressure (Pa)

Subscripts

f	feed solution
p	permeate side
w	solution adjacent to the surface of nanofiltration membrane

theory with the Spiegler-Kedem model for the calculation of NaCl concentration on the surface of NF 90 membranes. Simulated results were compared to the experimental data for validation. Secondly, permeation effects were used to calculate the surface coverage of polystyrene beads on the surface of the membrane using a model previously described by Cao et al. [11]. By using surface energy measured by Chen and Strevett [18], the polystyrene beads were used as a surrogates for bacterial cells in order to remove extraneous variables in the hydrodynamic model such as the effect of cell growth/death.

2. Materials and methods

2.1. Pure water and sodium chloride 0.1 M solution

The water used in the project was Grade 1 pure water (18.2 MΩ cm^{-1}) produced from an Elga Process water system (Biopure 15 and Purelab flex 2, Veolia, Ireland), hereafter referred to as MilliQ water. The high standard quality of water facilitates the repeatability of the experiments [7]. MilliQ water was used for pure water flux measurements and the preparation of 0.1 M sodium chloride (Sigma-Aldrich, Ireland) solutions for mass transport experiments.

2.2. Model foulant

Green fluorescent carboxylate micro-beads (Sigma, L4530) of 2 μm diameter were used for all adhesion experiments. A concentrated microbead solution was first diluted (1:30) MilliQ water. The suspension was then centrifuged at 10,000 RPM for 10 min. The supernatant was carefully discarded and the micro-bead resuspended with 25 ml of MilliQ. This sequence was repeated three times to remove any trace of surfactants from the solution the micro-beads were provided in. Prior to adhesion experiments, micro- bead pellets were re-suspended in the 0.1 M NaCl solution. The number of microbeads, as well as their fluorescence in solution, was verified and quantified by flow cytometry. This enabled adjustment to a standard microbead concentration to approximately 2.8×10^{11} micro-beads/L.

2.3. Filtration membrane

Polyamide composite flat sheet NF90 membranes (Dow Filmtec, USA) were used in this study. Membrane samples of 25 cm × 4 cm dimensions were cut from a large flat sheet roll, rinsed and soaked in MilliQ water overnight at 4 °C to remove any residual preservative layers. Membranes were then rinsed in MilliQ prior to compaction with MilliQ water for 15 h under 15 bar gauge.

2.4. Membrane fouling simulator and cross-filtration system setup

A schematic cross-sectional view of a Membrane Fouling Simulators (MFS) used in this study is illustrated in Fig. 1. The total active membrane area was 250 mm (*l*) × 40 mm(*w*). The depth of the channel was 0.8 mm. There were two permeation collectors located below the

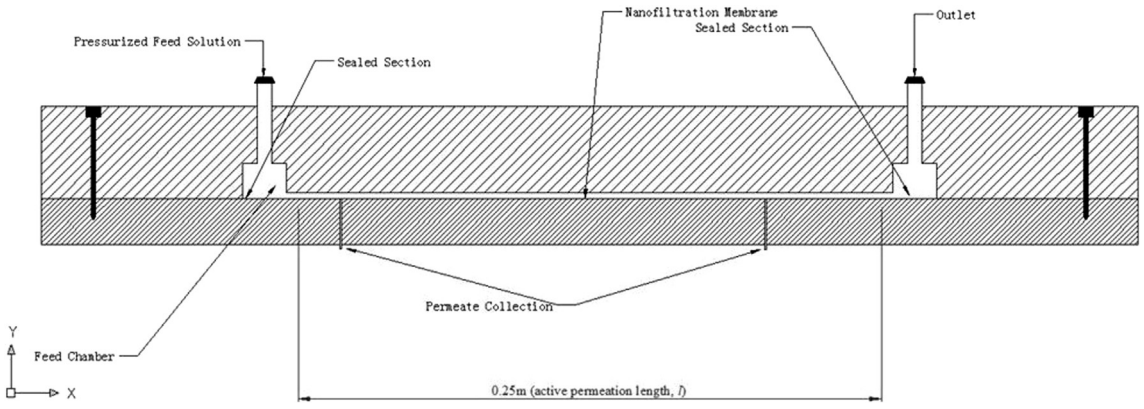

Fig. 1. Cross-sectional schematic of the membrane fouling simulator.