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Actuation of spatially-varying boundary conditions for reduction of concentration polarisation in reverse osmosis channels

Pesila Ratnayake, Jie Bao *

School of Chemical Engineering, The University of New South Wales, UNSW, Sydney, NSW 2052, Australia

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ABSTRACT

Reduction of concentration polarisation is of great value in reverse osmosis membrane systems. Concentration polarisation leads to a reduction in flux, which corresponds to a reduction in separation efficiency. This paper studies an approach by which to reduce concentration polarisation in reverse osmosis channels using a steady, spatially variant slip velocity profile. A method is developed to identify the most effective wall slip velocity profile for increasing the diffusive driving force away from the wall, which in turn increases mass transfer away from the membrane and reduces concentration polarisation. The nonlinear partial differential equations (PDEs) that govern fluid and mass transport behaviours are difficult to solve. In this work, an approximate solution to the nonlinear system is developed using systems of linearised ordinary differential equations (ODEs) to approximate the behaviour of the PDEs and determine the steady-state actuation profile that most effectively increases mass transfer at the wall. This leads to a systematic method for determination of a spatially-varying actuation profile (the most effective slip velocity profile) that decreases concentration polarisation in reverse osmosis membrane channels.

1. Introduction

Reverse osmosis is a major component of water treatment, and is particularly important in treatment of water with high concentrations of monovalent salts such as sea water and brackish water (Chen et al., 2004). As fluids move through semipermeable membranes from the feed channel into the permeate channel, solutes rejected by the membrane remain in the feed channel (Alexiadis et al., 2005). This leads to a buildup of solutes close to the membrane surface, known as concentration polarisation (Alexiadis et al., 2005; Chen et al., 2004). The concentration polarisation layer accumulates until the rate of convective movement of solutes towards the membrane balances the convective downstream movement of solutes close to the membrane surface, the diffusive mass transport away from the membrane surface, and any movement of solutes through the membrane (Fimbres-Weihs and Wiley, 2010). Concentration polarisation is associated with an increased osmotic pressure on the feed side of the membrane, resulting in a decrease in permeate flux and therefore decreasing the efficiency of the pressure-driven separation (Alexiadis et al., 2005). Additionally, concentration polarisation is a cause of fouling in membrane systems, which leads to membrane damage and reduced permeate flux (Alexiadis et al., 2005; Chen et al., 2004). Therefore, methods to reduce concentration polarisation are of great value.

A method by which fluid and solute behaviour can be altered is hydrodynamic manipulation, wherein the fluid flow profile is directly manipulated either by application of body forces (Du and Karniadakis, 2000) or by changing the flow profile at the boundary (Jovanović, 2006). Hydrodynamic boundary manipulation is typically achieved using techniques such as wall-tangential (forcing fluid to move along the wall) and/or wall-normal actuation (injecting or removing fluid at the wall). Wall-tangential actuation can be achieved by electro-osmosis, moving walls such as rotating cylinders, or appropriately angled fluid jets. Wall-normal actuation has been proposed using fluid jets at the wall to add fluid to and/or remove fluid from the channel.

Several approaches have been used in order to study and control fluid flow (Aamo and Krstic, 2003). D'Alessandro et al. (1999) developed an algorithm by which they maximised entropy in fluid flow as a measure of mixing. Armaou and Christofides (2000) developed a nonlinear controller for wave suppression, based on the Korteweg–de Vries–Bergers and Kuramoto–Sivashinsky equations, using distributed

* Corresponding author.
E-mail address: J.Bao@unsw.edu.au (J. Bao).

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actuators. By further study, Christofides and Armaou (2000) showed that the maximum number of actuators required for stabilisation of the Kuramoto–Sivashinsky equation is 5, subject to the value of the "instability parameter." Baker et al. (2000) developed a nonlinear controller for stabilisation of Burgers' equation and the 2D Navier–Stokes equations for incompressible flow using Galerkin's method and approximate inertial manifolds to derive systems of ODEs. Bamieh et al. (2001) achieved maximisation of mixing for both finite and infinite time horizons, based on a linear time-invariant system by using a linear quadratic (LQ) formulation to find the H_∞-norm of the system and a maximising feedback controller. Aamo et al. (2003) developed flow destabilisation by reversing the sign of a Lyapunov-based stabilising controller. Balogh et al. (2005) developed a method by which to maximise a mixing index using wall-normal actuation in 3D pipe flow based on an optimal Lyapunov-based control law. Ouyang et al. (2013) maximised an objective function related to fluid mixing using a pseudo-feedback approach that finds the most effective electro-osmotic input waveform. A major limitation of the bulk of work done on flow control with distributed actuation with respect to mass transport is that solute behaviour is not directly controlled, and solute mixing is assumed to have improved based on an increase in hydrodynamic mixing or a more even distribution of non-diffusive tracer particles.

Previous work by Liang et al. (2014) studies the effect of wall-tangential slip velocities on mass transfer at the membrane wall, as well as friction factor and permeate flux under steady-state conditions. The slip velocity profiles studied included uniform slip velocities, both in the streamwise (downstream) and the upstream directions, as well as non-uniform profiles created by electro-osmosis using 2 cylindrical electrodes with equal and opposite charge located under the membrane channel. They found that streamwise uniform slip velocities increased mass transfer and permeate flux and decreased friction factor, while upstream uniform slip velocities had the opposite effect (Liang et al., 2014). Similarly, for non-uniform profiles, increased mass transfer and permeate flux and decreased friction factor were observed in regions where the slip velocity was in the streamwise direction, with the opposite effect observed in regions where the slip velocity was in the upstream direction (Liang et al., 2014). Additionally, the non-uniform slip velocity profile tended to have a larger effect than the uniform slip velocity profile. However, these profiles were designed based on simplicity of analysis (uniform) and simplicity of actuation (non-uniform). Therefore these profiles are likely to be suboptimal, and may be improved by optimisation of the slip velocity profile.

Partial differential equations (PDEs) are often converted into infinite-dimensional systems of ordinary differential equations (ODEs) by spatial discretisation or decomposition into an infinite set of basis functions (Curtain and Zwart, 1995; Callier and Winkin, 1992; Moghadam et al., 2014, 2012, 2013). This allows for systems governed by PDEs to be approximated and studied using techniques developed for systems of ordinary differential equations. Previous work by the authors of this paper used linearised models of 2D laminar channel flow to find the most effective spatially and temporally oscillatory wall-tangential velocity profile for velocity oscillations in regions of the fluid (Ratnayake et al., 2015).

Other numerical studies consider reduced-order approaches for heat and mass transport, as well as reactor systems. Adomaitis (2003) developed an approach for study of distributed parameter systems by producing trial functions for reduced-basis discretisation, studying chemical vapour deposition as an example. Reduced order approaches allow for significant reductions in computational load by determining or focusing on the spatial modes that have the largest effect on the system behaviour (Adomaitis, 2003). Setiawan et al. (2015) developed a reduced order model for mass transport behaviour in membrane channels using reverse osmosis by limiting the number of spatial modes studied and approximating the hydrodynamic behaviour as static. This greatly reduced computation time whilst achieving similar simulation results to nonlinear computational fluid dynamics (CFD) approaches. However, these approaches are limited by their operating conditions, and modelling far from the one predefined steady state can lead to significant error.

Yao et al. (2010) developed an approach for computation of cyclic steady states in oscillatory or periodic processes, using an integration scheme as well as prediction and correction in order to efficiently determine the behaviour of the system at each period. This approach was able to accurately predict the steady-state behaviour of oscillatory distributed parameter systems, but requires online measurement in order for the integration to be conducted accurately. Yao et al. (2013) developed a networked model predictive control (MPC) approach to regulate distributed parameter systems, using the dominant eigenmode and the Galerkin method to convert the system into an ODE. This approach was able to effectively control the diffusion-reaction process presented, using either static or adaptive communication policies, but requires online measurement for feedback control.

Concentration polarisation is of great interest in reverse osmosis membrane systems because it contributes significantly to the operational costs of producing water. Song et al. (2003) showed that for high concentration feeds, such as those in seawater desalination, concentration polarisation can have a significant impact on permeate flux. Zhu et al. (2009a) discussed the importance of considering concentration polarisation and the osmotic pressure at the membrane surface when calculating the minimum operating (transmembrane) pressure required in order to achieve flux through the membrane length. Zhu et al. (2009a,b, 2010) develop a number of cost optimisation strategies for reverse osmosis membrane systems and plants, noting that concentration polarisation impacts on costs by increasing the required cross-flow velocity. Additionally, they note that mineral scaling and fouling form constraints to the optimisation of permeate flux (Zhu et al., 2009a).

Many nonlinear distributed parameter systems such as membrane systems, heat exchangers and chemical reactors can be improved by using distributed boundary actuation, since distributed boundary actuation can be used to redirect flow to achieve better performance. However, these systems often lack real-time distributed measurement. This is particularly the case for measurement of concentration. Whilst some new technologies such as electrical resistance tomography (ERT) have been shown to provide distributed real-time measurement (Sharifi and Young, 2011), applications of such technologies are limited to date. Therefore, this paper proposes a novel approach for changing steady states in nonlinear distributed parameter systems using spatially-varying boundary actuation without requiring online measurement. This is demonstrated by decreasing steady-state concentration polarisation using slip velocities applied at the surface of a reverse osmosis membrane. By performing steady-state analysis on successive locally linearised state-space equations, a small, spatially-variant steady-state perturbation slip velocity profile is calculated such that it provides the greatest increase in mass transfer away from the wall per unit slip velocity input. By applying the small perturbation, a new (nearby) steady state is reached. By repeating this process at each successive steady state, a large increase in overall mass transfer coefficient is achieved. This approach approximately determines the perturbation slip velocity profile that has the greatest effect of increasing mass transfer at the wall. This paper also proposes a new, generalised infinite-dimensional linearised model of hydrodynamics and mass transfer in 2D channel flow. This generalised linearised form allows for fast simulation and analysis about any given steady-state profile. A new method is proposed in this paper by which to identify the most effective tangential wall (slip) velocity profile for reduction of concentration polarisation by increasing the diffusive driving force