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Reduced-order model for the analysis of mass transfer enhancement in membrane channel using electro-osmosis

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HIGHLIGHTS

- A reduced-order model on mass transfer enhancement caused by electroosmotic flow is developed.
- It combines the discretized mass transfer and linearized Navier–Stokes equations.
- Most effective temporal activation frequency is identified using frequency response analysis.

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ABSTRACT

Flow control has the potential to mitigate concentration polarization and fouling in membrane systems by enhancing mixing near the membrane surface. Although Computational Fluid Dynamics (CFD) modeling has been used to study the effect of externally induced unsteady flow on mass transfer enhancement, the analysis based on CFD results is computationally expensive and cannot be performed systematically. Existing systematic approaches to quantify mixing enhancement only consider hydrodynamics but not the direct effect on mass transfer improvement, due to the difficulties caused by the non-spatially invariant nature of the mass transfer phenomenon. This paper presents a reduced-order model that combines the discretized mass transfer and linearized Navier–Stokes partial differential equations. The proposed model can be used to simulate and systematically analyze mass transfer enhancement caused by the flow induced by a pair of electrodes. When the Reynolds number and temporal frequency of the external field are low ($Re < 2000$), the effect of a forced wall slip velocity on the overall flow profile in a 2D channel can be approximated by its instantaneous component. This allows mass transfer enhancement to be analyzed explicitly using a discretized mass transfer equation. The results predicted by the reduced-order model are in good agreement with CFD simulations. The benefit of the proposed reduced-order model is demonstrated by the frequency response analysis to identify the temporal frequency that has the maximum effect on mass transfer enhancement.

1. Introduction

Membrane separation is widely used in industrial processes including water treatment and desalination. Concentration polarization, which may lead to the onset of fouling, reduces the flux through the membrane or increases the trans-membrane pressure required to achieve a desired permeate flux. This translates to increased operating costs and reduced membrane system performance. Existing methods to minimize concentration polarization and fouling include bulk velocity control, eddy promoters, membrane surface/material modifications, and external activation fields. The external field method has significant potential for implementation because it can be applied independent of the velocity and membrane modifications (Nadh Jagannadh and Muralidhara, 1996). Applying an external field near a membrane surface can potentially disrupt the concentration boundary layer and enhance mass transfer (by increasing mixing) and therefore, reduce concentration polarization/fouling (Ouyang et al., 2013; Liang et al., 2014b).

Aamo et al. (2003) proposed a method for mixing enhancement through the application of feedback control on a 2D channel boundary layer. The work has also been successfully extended to 3D pipe flow (Balogh et al., 2005). It has been shown that by properly controlling the flow system, mixing can be improved considerably using only a small control effort, implemented through flow suction and injection across the wall (Aamo and Krstić, 2003). Schuster et al. (2008) studied the mixing enhancement of electrically conducting fluids moving in an

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electromagnetic field. The effect on heat transfer improvement of the fluids under electromagnetic field actuation was also presented (Luo and Schuster, 2006). However, existing mixing enhancement studies that utilize flow control only consider the fluid dynamics while excluding the underlying mass and heat transfer phenomena in the problem formulation. In most cases, fluid mixing enhancement does not translate to the same degree of mass and heat transfer improvement. Furthermore, ignoring the mass and heat transfer equations means that it is impossible to quantify the transfer enhancement directly.

In the case of membrane systems, it has been shown that the formation of a particle fouling layer can be slowed or eliminated through pulsatile flow (Rodgers and Sparks, 1992; Li et al., 1998; Alexiadis et al., 2005). Dynamic/oscillatory shear is often applied to membrane systems using ultrasound, a rotational disk or a vibrational membrane surface (Kola et al., 2014). High-amplitude shear oscillations are more effective than shear alone and it is expected to also reduce the ion concentration build up at the membrane surface (Antony et al., 2011). This is because during high shear periods, more particles or ions can be removed or prevented from reaching the membrane due to shear-induced diffusion (Davis and Leighton, 1987; Belfort et al., 1994; Romero and Davis, 1990), hindering the development of a stagnant cake or concentration layer (Romero and Davis, 1990). Moreover, shear forces can erode and limit the growth of biofilm layers, which are one of the main causes of flux decline in membrane systems (Flemming, 1997). Therefore, oscillating flow disturbances have the potential to increase the critical flux (Field et al., 1995) and thus increase the long term stability of permeation. The method proposed in this paper is able to quantify the effect of externally induced oscillatory flow near a membrane surface on the magnitude of concentration boundary layer oscillations, thereby affecting concentration polarization and fouling.

The actuation method considered in this paper is electro-osmosis, which is generated through the application of an electric potential gradient near a charged solid/liquid interface, causing liquid to flow with respect to the adjacent charged surface (Nadh Jagannadh and Muralidhara, 1996). Electro-osmotic flow induced near a membrane surface can potentially lift particles or ions from the surface by enhancing the mixing near the wall, which otherwise has zero velocity (assuming a 'no-slip' condition on the wall). Electro-osmosis can be classified as a type of flow control, defined as the manipulation of fluid flow into a desired behavior with the purpose of enhancing mixing or suppressing turbulence. Flow control can be implemented using different control strategies, including active, passive, open-loop and closed-loop (Kim and Bewley, 2007; Aamo and Krstić, 2003). Recent integration of different disciplines including control theory, fluid mechanics, Navier–Stokes (NS) mathematics and numerical methods has promoted flow control into an active area of research (Bewley, 2001). Reduced-order models had been used previously for the system analysis and control design of fluid flow systems which are described by the partial differential Navier–Stokes (Baker et al., 2000; Armaou and Christofides, 2000). In this paper, model-reduction is extended beyond the Navier–Stokes equations into the mass transfer equation. For a 2D reverse osmosis channel, the model allows a systematic system analysis, in terms of quantifying the effect of an externally applied electric field using two electrodes on mass transfer enhancement near the membrane surface, therefore improving permeate flux and assisting fouling mitigation. Moreover, the model can also be used for systematic control design because it is represented as a linear time invariant system. It should be noted that the proposed method is not limited to this configuration, but can be extended easily to more complex geometries.

In comparison to the bulk flow, the perturbation velocity induced by the electro-osmotic flow is relatively small and therefore the hydrodynamics can be approximated using linearized NS-equations. Linearization is performed by neglecting the high-order terms of the perturbation velocity and its gradient in the NS-equations. Furthermore, the linearized system can be discretized in the spatial directions using Fourier–Galerkin and Chebyshev collocation methods (Zhang et al., 2008). The hydrodynamics can then be expressed by a set of ordinary differential equations (Aamo and Krstić, 2003).

In this paper, a similar procedure is applied to the mass transfer equation. The combination of both the linearized and discretized Navier–Stoke and mass transfer equations then allows the effect of input electric potential on mixing enhancement in the channel to be analyzed systematically. A distinct feature of this work is that the method of analysis is developed based on the non-spatially invariant combined NS-mass transfer equation which is inherently nonlinear spatially (Dubljevic et al., 2005; El-Farra et al., 2003). In this paper, the mass transfer enhancement in a membrane system is incorporated in the form of a dissolving wall (i.e. no permeation) boundary condition (Schwinge et al., 2002; Fimbres Weihs et al., 2006). Although a permeable wall boundary condition (Fletcher and Wiley, 2004; Arun et al., 2006; Fimbres Weihs and Wiley, 2010) in which the wall mass fraction is dependent on the permeation velocity would be more physically accurate, the relative magnitude of the permeation velocity is usually a few orders of magnitude smaller than the average fluid velocity, such that the effect of permeation on wall shear and mass transfer enhancement is minimal (Ndinisa et al., 2005). In addition, for channel geometries and flow conditions typically found in nanofiltration and reverse osmosis, Geraldes and Afonso (2006) have demonstrated that mass transfer coefficients obtained for cases without permeation can be used to predict the wall conditions in cases where permeation is present. The impermeable-dissolving wall model is therefore capable of providing valuable insights into the electro-osmosis induced mass transfer phenomena taking place inside narrow channels without the need to explicitly model permeation, and the results obtained should still represent a good approximation of the flow and mass transfer in actual membrane systems.

In our previous work, the fluid dynamics of the electro-osmotic flow was simulated using Computational Fluid Dynamics (CFD) software (Liang et al., 2014b). However, an analysis to quantify the relationship between the input electric potential and the measurements (such as perturbation velocity and solute concentration) cannot be carried out systematically using the CFD results. In this paper, a frequency response analysis is proposed based on the reduced-order model of the Navier–Stokes and mass transfer equations. It can systematically analyze the effectiveness of electro-osmosis at different locations in a 2D channel that operates under different oscillation frequencies, electrode configurations and flow conditions, including the *Re* and *Sc* numbers. Moreover, the reduced-order model can be used to simulate the response of solute concentration to electro-osmosis and potentially used for flow control design.

2. System description

This study considers a 2D rectangular channel with a membrane installed on the lower wall, as shown in Fig. 1. A solvent is fed into the channel at a constant rate with a fully developed parabolic steady-state flow profile. The dissolving wall model used in this paper assumes that the lower wall of the channel has a constant solute concentration, which leads to a single-species developing concentration boundary layer (Fimbres Weihs et al., 2006). The paper focuses on the laminar flow region ($Re < 2000$), for which mixing enhancement is important. The extended inlet and outlet regions are added to ensure that boundary conditions of the real system will be properly represented by the proposed reduced-order