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CFD modelling of electro-osmotic permeate flux enhancement on the feed side of a membrane module

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ABSTRACT

Electro-osmosis has the potential to enhance mass transfer at the membrane surface, thereby minimising concentration polarisation, particularly for nanofiltration and reverse osmosis processes. Electro-osmotic flow can result in a disruption of the concentration boundary layer because of the movement of a thin layer of fluid in the vicinity of the membrane surface. A Computational Fluid Dynamics (CFD) model is used to simulate steady electro-osmotic flow with permeation inside a 2D unobstructed empty membrane channel. It is found that a slip velocity in the direction of bulk flow results in permeate flux enhancement, while a slip velocity in the opposite direction results in flux decline. A non-uniform slip velocity shows greater permeate flux enhancement than a uniform slip velocity. In addition, the results show that electro-osmosis is more effective in enhancing flux for systems with a higher level of concentration polarisation (low Reynolds number and/or high Schmidt number). The data suggests that for seawater RO, electro-osmosis is more effective as the permeability of the membrane is increased, and reaches a peak in the permeability range of brackish water RO membranes. The data also reveals better electro-osmotic enhancement for membranes with lower intrinsic rejection, which might be particularly suited for ultra-osmosis.

1. Introduction

Over the past decades, there has been increasing interest in membrane technology for water treatment due to a growing demand for high quality water and growing pressure to reuse waste water [1]. However, a major issue associated with these membrane operations is concentration polarisation. Concentration polarisation reduces membrane performance through an increase of the osmotic pressure at the membrane surface, thus increasing the pressure driving force required. Another adverse effect of concentration polarisation is that it promotes membrane fouling. The fouling phenomenon results in greater resistance to solvent flux, which further deteriorates membrane performance.

Numerous techniques have been proposed to minimise the effects of concentration polarisation, with much investigation going into the optimisation of spacer geometry and configuration for spiral wound module (SWM) applications, particularly for reverse osmosis (RO) [2]. Electro-osmosis, which is the transport of fluid resulting from ionic movement within an electric field, has been proposed as a technique for enhancing mass transfer on the feed side of the membrane, therefore increasing permeate flux [3]. Electro-osmosis may be especially applicable for desalination and some types of water treatment with ionic species, because saline water contains charged species that can respond to an electric field.

Electro-osmosis has found numerous applications in microfiltration and ultrafiltration processes [4–14]. In spite of this, only a handful of researchers have applied this technique to RO processes [15,16]. Spiegler and Macleish [15] were the first to apply the electro-osmosis technique to RO processes for the desalination of a process stream contaminated with ferric hydroxide. They found that electro-osmotic backwashing of the membrane resulted in a significant recovery (30–100%) of flux loss. However, the mechanisms that lead to mass transfer enhancement within the concentration polarisation layer are not yet fully understood.

Recently, computational fluid dynamics (CFD) has improved the understanding of hydrodynamics and mass transfer in membrane processes [17–19]. CFD is capable of providing large amounts of data at any point in a membrane channel, which can be used to assess the performance of the membrane unit without altering or changing the flow. CFD is therefore an efficient tool for performance assessment in terms of time, cost and the risk associated with carrying out repeated experiments [20,21].

The question of validation of CFD predictions by experimental data is a crucial one. Particle image velocimetry (PIV) can provide

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useful information about complex fluid flow fields, and has been proven to be applicable for microchannel systems with low Reynolds numbers (usually much less than 100) [22]. However, PIV is significantly limited for visualising higher flow rates and velocity gradients such as those found in the very thin boundary layer of membrane channels. This is mainly because of the video framing rate and poor video resolution limit of PIV under these conditions [23]. In typical RO processes, the average velocity of the bulk fluid is of the order of 0.1–1 m/s, while the typical electro-osmotic velocity is of the order of 10^{-4} m/s [24]. This gives rise to difficulties in visualising the electro-osmotic flow trends, especially within the concentration polarisation boundary layer region in RO systems.

In our previous work [25], we presented a simplified approach for modelling electro-osmosis within the boundary layer of membrane systems. This modelling technique, known as the Helmholtz–Smoluchowski (HS) approach, incorporates electro-osmotic flow as a forced slip velocity at the membrane surface and takes into account only the electric field in the direction tangential to the membrane and not the normal component. The HS approach was validated against a more rigorous charge density (CD) approach and they were found to be in good agreement for typical concentration and flow conditions encountered in RO SWM modules.

The effect of a slip velocity on mass transfer and pressure drop has been the focus of a few studies in the context of ultrafiltration (UF) processes [26]. This is because the porosity of UF membranes leads to a slip velocity at the membrane surface. Beavers et al. [27] found excellent agreement between experimental data and the analytical solution of the Navier–Stokes equations for a 2D unobstructed empty channel under the influence of a slip velocity. Singh and Laurence [28] developed a perturbation solution for the velocity profiles in a 2D unobstructed empty channel subject to permeation from both walls. The perturbation solution was then used to obtain numerical solutions for the mass transport equation. They found that an increase in slip velocity results in decreased friction factor and increased mass transfer. In addition, they observed that the slip velocity induced mass transfer enhancement is greater in the region closer to the membrane entrance, and for solutes with lower diffusivity. Despite these findings, the effect of slip velocity on mass transfer has not been studied in the context of RO.

While there are some recent studies on the use of electro-osmosis for mixing [29,30], none of them have focused on the reduction of concentration polarisation and fouling at the surface of a membrane. Although previous studies have simulated the effect of electro-osmosis on the hydrodynamics [25,30], they have not incorporated mass transfer or the effect of electro-osmosis on permeate flux. Moreover, CFD membrane studies in the literature have mainly focused on the optimisation of spacer geometry and configuration for SWM applications [21,31–36], or other physical approaches for mass transfer enhancement [37–39], and have not considered the effect of electro-osmosis.

This paper therefore uses CFD to investigate the role of electro-osmosis in enhancing mixing at the membrane surface. For this purpose, electrodes are assumed to be located in the vicinity of the membrane surface, on the permeate side, so that the electric field is localised within the feed-side boundary layer. The effect of this electric field in terms of boundary layer disruption and consequent increase in mass transfer and permeate flux are then analysed. This paper extends our previous work [25], focusing on understanding the mechanisms that lead to electro-osmotic mass transfer enhancement in steady-state alone. It analyses the effect of membrane properties and bulk flow conditions under constant transmembrane pressure, in order to identify the conditions under which electro-osmosis is effective for enhancing mass transfer and permeate flux. Consideration of unsteady effects such as caused by the presence of spacers is beyond the scope of this paper.

2. Problem description, assumptions and methods

2.1. Model description

CFD ANSYS CFX-13.0 is used to solve the steady-state continuity, momentum and mass transfer equations. As in our previous studies, constant properties are assumed and the effect of gravity is excluded [40,41]. In addition, the fluid is assumed to be Newtonian and the flow two-dimensional (2D). The channel geometry used is depicted in Fig. 1. Entrance and exit regions are included at each end of the channel in order to ensure that the flow solution is not affected by the inlet and outlet boundary conditions [17–19].

2.1.1. Boundary conditions

The channel walls in the entrance and exit regions, as well as the top channel wall in the membrane region are treated as non-slip with no mass transfer ($u=v=0$ and $\partial\omega/\partial y=0$). On the membrane surface (bottom wall of membrane region) the velocity component boundary conditions are given by the electro-osmotic forced slip velocity ($u=u_s$) and permeate flux ($v=v_w$) respectively. Moreover, the mass fraction boundary condition is obtained from the mass balance for the solute at the membrane. These boundary conditions are discussed in more detail below.

Our previous work [25] concluded that the electric field normal to the membrane surface had a negligible effect on the flow field. Hence, only the electric field tangential to the membrane surface is considered in this paper. The HS forced-slip velocity along the membrane surface (the “slip velocity”) is therefore expressed as

$$u_s = -\frac{\varepsilon\zeta E_x}{\mu} \tag{1}$$

where the electric field tangential to the membrane surface (E_x) for the electrode configuration shown in Fig. 1 is given by [25]

$$E_x = \frac{V}{2\ln((x_{e2}-x_{e1}-r_e)/r_e)}\left[\frac{x-x_{e1}}{(x-x_{e1})^2+(r_e+h_m)^2}-\frac{x-x_{e2}}{(x-x_{e2})^2+(r_e+h_m)^2}\right] \tag{2}$$

Eq. (2) is the analytical solution for the electric field, assuming the permittivity is uniform. Variations in permittivity due to membrane properties or the location of the membrane and the electrodes can influence the electric field and, therefore, the slip velocity experienced on the membrane surface. For the case of an RO system, the support layers of the membrane make up most of the membrane thickness. Due to the high porosity of these layers, their permittivity value can be considered similar to that of water [42]. In addition, the selective layer of the membrane is very thin (as thin as 1×10^{-7} m or less) [43], so the effect of the permittivity of this layer can be assumed to be negligible. Thus, for simplicity, this paper neglects effects associated with the nonuniformity of permittivity. In the general case of non-uniform permittivity and arbitrary electrode geometry and position, the electric field must be obtained numerically.

In addition to the non-uniform electric field produced by the electrodes shown in Fig. 1, we also consider a uniform electric field. Fig. 2 shows a schematic of the uniform and non-uniform

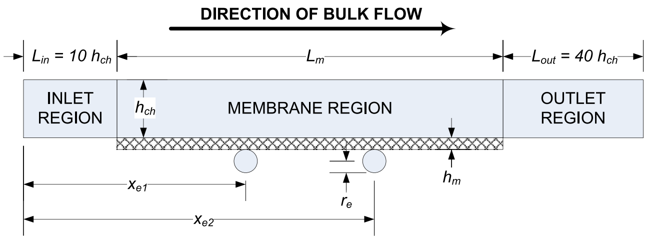

Fig. 1. Geometry used in ANSYS CFX-13.0 to model 2D empty rectangular channel.