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Visualization and modeling of the polarization layer in crossflow reverse osmosis in a slit-type channel

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ABSTRACT

The evolution of the concentration polarization layer during crossflow reverse osmosis in a slit channel has been studied. Digital Holographic Interferometry allows visualizing the polarization layer as an interference fringe pattern. An especial module with four windows has been designed to see the development of the polarization layer along the membrane channel. Several experiments with a constant transmembrane pressure of 6 bar, three different feed concentrations (3, 6 and 9 kg/m^3) and three different Re (13, 38 and 111) had been carried out. The process has been modeled simulating the experimental conditions. The computed results were found to be consistent with the experimental ones. All the experiments show a continuous increase of the polarization layer along the channel, regardless of the crossflow velocity, except near the outlet of the cell due to an edge effect. This increase in the polarization layer is greater at lower Re, although it does not influence very much the permeate flux. In contrast, what substantially affects the permeate flux, much more than Re number, is the feed concentration due to its osmotic pressure.

1. Introduction

Rejection of salt ions at the membrane surface in reverse osmosis processes (RO) leads to an increase in solute concentration near the membrane. This phenomenon is called concentration polarization (CP) and is one of the most important factors influencing the performance of membrane separation processes [1]. Concentration polarization is the primary reason for flux decline during the initial period of a membrane separation, due to an osmotic pressure raise. In addition, CP can be also the precursor of subsequent fouling mechanisms in RO [2,3]. Knowledge and prediction of the concentration polarization effects, therefore, is crucial for designing reverse osmosis processes, predicting their performance, and especially for understanding the surface fouling phenomena [2,4,5].

The development of the CP layer in cross-flow RO is a complex process that is influenced by several factors such as solute properties, membrane properties and hydrodynamics (flow conditions, pressure, geometry of the channel, etc.) [6,7]. To properly predict the phenomena, it is necessary an accurate description of the variables involved in the CP development, although there is still a debate to state the most appropriate way to predict the concentration polarization in RO and in other membrane separation processes [4].

In a RO process, concentration polarization is coupled with permeate flux: CP is induced by permeate flux, which brings solute to the membrane but, at the same time, the permeate flux is limited by the resistance due to CP [4,6]. Besides this statement, in crossflow RO appears another fact that must be considered. As a result of solute continuous entrance to the membrane channel and solute rejection and accumulation, the concentration polarization layer grows gradually along the filtration channel [5,6,8,9].

Sablani et al. [8] made a critical review of works about concentration polarization in ultrafiltration and RO. Most of the papers were basically focused on theoretical studies or computational simulation of those processes. More recent studies have followed the same way and thus there is a lack of experimental research measuring the CP layer. The theoretical studies have made attempts to develop mathematical models for predicting the CP level in a membrane system. Some researchers use the classical film theory, which requires the knowledge of a mass-transfer coefficient, using a model that considers the mass transfer equations in the proximity of the membrane surface. Some of them assume a uniform solute concentration and permeate flux over the membrane surface [10] but others consider these variables as channel length dependent [6,11,12].

During the past decades the computational simulation of membrane processes became very popular due to the increasing

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computational power that allowed solving the mass transfer equations coupled with the governing transport equations by using numerical methods. Computational Fluid Dynamics (CFD) provides a powerful tool to determine the flow pattern adjacent to the membrane surface. A comprehensive review about the CFD methods applied to membrane processes has been made by Ghidossi et al. [13]. Most studies were made under laminar conditions since most of the membrane processes work under these conditions [14–17]. The slit-type configuration represents the basic model to characterize the flow in industrial membrane modules, thus restricting the flow to laminar conditions and causing severe problems of CP. Geraldes et al. [18] proposed a correlation between the concentration and the hydrodynamic boundary layer thickness which gives an insight into the mechanisms involved in the growth of the boundary layers in the nanofiltration (NF) processes. Wiley and Fletcher [19] proposed a general purpose CFD model of concentration polarization and fluid flow. The model was extended to examine buoyancy effects in the salt water system under reverse osmosis conditions [20]. All these models show a trend towards greater completeness intending to enhance the performance of membrane separation processes.

Therefore, the accurate characterization of the build up and evolution of the CP layer is essential to fully understand the fouling mechanisms in RO processes. Different techniques for in situ monitoring the polarization phenomena in a membrane system have been developed over the years [21]. However, only a few papers can be found in which the concentration polarization layer is measured directly.

Interferometric techniques are one of those techniques cited by Chen et al. [21] that can be used to fully observe the CP. Digital Holographic Interferometry (DHI) has been used in this research and was previously applied to the study of the CP layer [22,23]. It is an interferometric technique very similar to classical Holographic Interferometry previously used [24–27] but replacing the holographic plate, which needs to be photographically developed, by the CCD chip of a video camera [28]. The interferometric techniques are based in the appearance of interference fringes related to changes in the refractive index of an object where a laser beam has passed through. Concentration polarization entails a change in the refractive index near the membrane surface. Therefore, the comparison of different states of the object studied (i.e. different images captured by the CCD) will cause the appearance of interference fringes, which will allow the visualization of the CP layer.

Both aforementioned aspects concerning concentration polarization in crossflow reverse osmosis (relationship between permeate flux and CP, development of the polarization layer along the membrane channel) are studied in this paper. Moreover, the use of an interferometric technique as DHI is a further step forward since it allows direct observation and measurement of the concentration profile within the concentration polarization layer as well as its evolution along the channel. This important information about the polarization phenomena notably improves those analytical works that use other experimental data (bulk concentration, flux and concentration of permeate, etc.).

This experimental research completes a previous one where concentration profiles and permeate fluxes in crossflow RO were studied [22]. A new longer module has been used to visualize the built up of the polarization layer along the membrane channel. The new module has four windows along the channel thus allowing the visualization of the concentration profiles at different locations of the membrane channel. The results obtained showed the tight relationship between CP, the permeate flux, the crossflow velocity and the development of the polarized layer along the permeation channel. The experimental conditions have also been simulated using a CFD model, developed to compute the permeate flux and the concentration profiles in order to check the evolution of the polarization layer along the membrane channel. The results predicted by the simulations are in reasonable agreement with the experimental ones.

2. Experimental

2.1. Experimental set-up

Two different systems are linked together in the experimental assembly: the optical set-up for DHI and the reverse osmosis system. Both systems are the same to that explained in a previous paper [22]. These two assemblies are coupled on the same work table, being the RO module the common element.

The RO cell is specially designed to carry out the crossflow RO process satisfying the Holographic Interferometry requirements. The module is similar to that described in a previous paper [22], but with some marked changes to allow the study of the evolution of the concentration polarization layer along the permeate channel. The main difference is its size, more than twice longer than the previously used module. The new one consists also of two independent parts connected by bolted joints (Fig. 1). The top part is a methacrylate cell, coated with a stainless steel housing to ensure physical stability. Pressure applied in the RO experiments could deform the transparent methacrylate cell, causing the appearance of interference fringes spurious to the concentration polarization. The stainless steel housing was used to avoid this possibility. The housing was provided with four circular windows, thus allowing the membrane surface to be visualized at different positions along the membrane channel.

The connection between the module and the reverse osmosis system is through a stainless steel tube of 4 mm of diameter. As the section of the tube and the channel are very different, an edge effect can disturb the flow through the module, especially in the windows closest to the inlet and outlet sides (windows one and four).

The membrane is placed in the bottom part, made of Teflon, and is fixed when both parts of the module are joined together, getting tightened between them. A porous plastic piece located

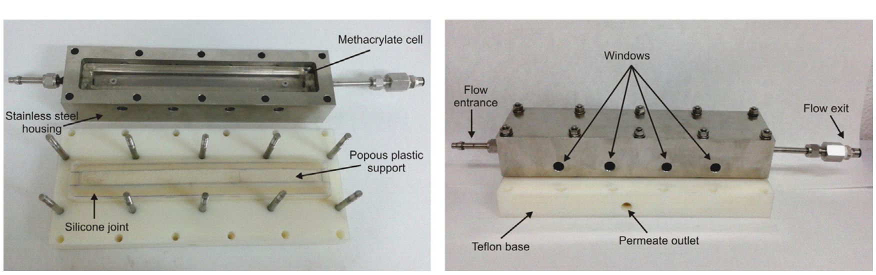

Fig. 1. RO module.