Book of Abstracts
European Congress of Chemical Engineering (ECCE-6)
Copenhagen, 16-20 September 2007

Hydrodynamics and concentration polarization in NF/RO spiral wound modules with ladder-type spacers: experimental and numerical work

Maria Norberta de Pinho,[a] Viriato Semiao,[b] Vitor Geraldes [c]

[a,c] *Department of Chemical and Biological Engineering,* [b]*Mechanical Engineering Department Instituto Superio Tecnico, Technical University of Lisbon, Av. Rovisco Pais, PT-1049-001 Lisbon, Portugal*

1. Summary

An intensive and consistent work, associating experiments to computational fluid dynamics (CFD), was performed aiming at the study of the influences of both fluid flow momentum and mass transfer phenomena on the concentration polarization in the permeation of aqueous solutions in spiral-wound modules. Several mechanisms were analyzed. First it was studied the effect of momentum boundary layer development in the mass transfer rates in open slits for nanofiltration (NF). Then, it was analyzed in detail the physical mechanisms governing the onset of both hydrodynamic and concentration boundary layers. After, the fluid phase modelling was integrated with that of the membrane transport, where the solute transport model inside the membrane was improved through the use of hindered transport mechanisms. Further integrated modelling was developed, paying particular attention to the solute hindered transport inside the membrane, making recourse to the steric-force pore flow model to calculate the membrane intrinsic rejection coefficient as a function of the pore Peclet number, which in turn depends on the membrane pore radius. The presence of ladder-type spacers was also investigated by analysing the effect of the geometrical parameters on the concentration boundary layer disruption.

Keywords: Nanofiltration, Boundary-layer disruption, CFD, Integrated modelling, pore flow modelling

2. Extended Abstract

Concentration polarisation has adverse effects on the membrane performance, namely the increase of the membrane fouling and the decrease of the productivity and the quality of permeate water. It is presently recognized that flow management is the most adequate way to control and minimise the concentration polarisation. Insight on

the detailed mechanisms inside feed channels of spiral-wound modules is required to systematically evaluate the limitation of the existing spacers and set new directions to develop new ones with enhanced geometry. CFD, supported by experiments, appears as an invaluable tool to address this task.

A home developed CFD code has been used to predict the fluid flow and the mass transfer in slits. This code solves the coupled continuity, momentum and solute conservation equations, together with the respective boundary conditions, including cyclic ones.

The test cell is made of two stainless steel and detachable parts that once attached create a thin rectangular channel 2 mm height, 30 mm width, and 200 mm long to ensure the two-dimensionality of the flow.

The study of the effect of momentum boundary layer development in the mass transfer rates in the above-described slit, for NF conditions (100<Re<1000, 1<ΔP<4 MPa, Sc=850), revealed that the entrance length in open channels is not influenced by permeation rates, depending only on the circulating Reynolds number, whereas the permeation fluxes depend also on the permeation Reynolds number [1]. For CFD modelling, previously validated against experimental data and benchmark problems [2], the intrinsic rejection coefficient was made to depend on the operating parameters: the transmembrane pressure, ΔP, and the permeation flux, v_p.

Then, the fluid phase modelling was integrated with that of the membrane transport and the range of studied Schmidt numbers was extended to 570<Sc<3200 [3]. The transport modelling of the solute inside the membrane was improved through the use of hindered transport mechanisms. The solution properties were allowed to vary with the solute concentration. Results showed that the concentration polarization depends on both the circulating and the permeation Reynolds numbers and on the Schmidt number. The following correlation for the concentration boundary layer thickness was obtained: $\delta_\omega / h = 15.5(l/h)^{0.4}\, Re^{-0.4}\, Sc^{-0.63}\, Re_p^{-0.04}\left[1 - 186\, Sc^{-1.0}\, Re_p^{-0.21}\right]$.

Moreover, it was analyzed in detail the physical mechanisms governing the onset of both hydrodynamic and concentration boundary layers, the onset of the former occurring prior to that of the latter [4], as shown in fig. 1.

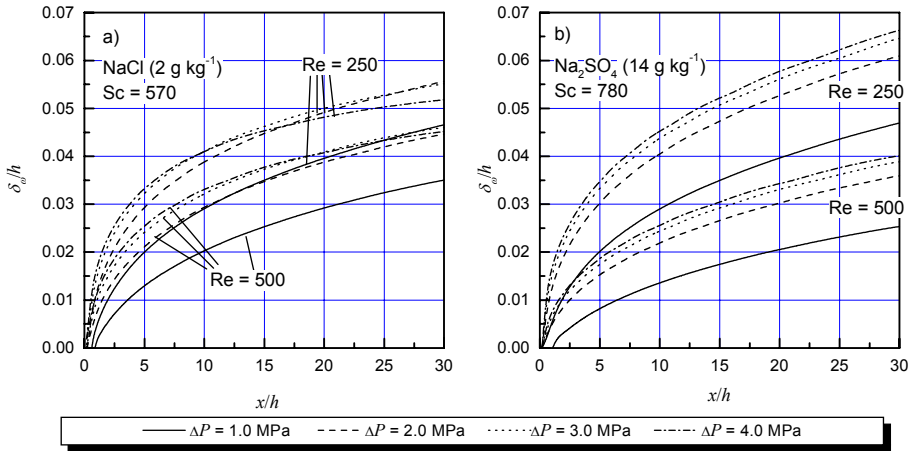

Figure 1 - Variation of the non-dimensional concentration boundary layer (δ_ω/h) with the non-dimensional distance to the slit inlet (x/h). Membrane - CFDNF50l.

The hydrodynamic boundary layer grows by molecular diffusion of momentum as a consequence of the non-slip condition at the membrane surface, this growth being insensitive to permeation fluxes and to Schmidt numbers in the range of interest of NF. Conversely, the concentration boundary layer growth depends on those two last parameters. The increase of the circulating flux yields an increase of the laminar shear stresses near the membrane surface that act as an enhancement factor to the solute transfer, slowing down the growth of the concentration boundary layer.

Further integrated modelling was developed, paying particular attention to the solute hindered transport inside the membrane, making recourse to the steric-force pore flow model to calculate the membrane intrinsic rejection coefficient as a function of the pore Peclet number, which in turn depends on the membrane pore radius [5].

The presence of ladder-type spacers was also intensively studied through the analysis of the effect of the geometrical parameters, spacers' height and distance, on the concentration boundary layer disruption. Figure 2 shows a few results of such study. It was concluded that the spacers' constitution must be such that concentration boundary layer disruption has to occur at both top and bottom membranes, otherwise, near the membrane without spacers adjacent to it, a continuously growing concentration boundary layer will develop [6]–[8], yielding an increasing concentration polarization.

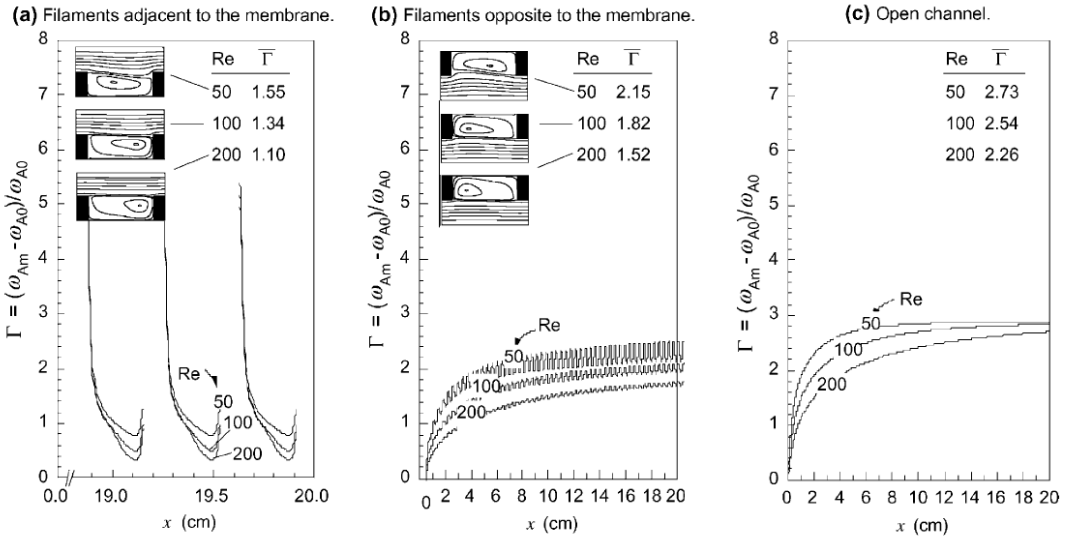

Figure 2 - Effect of the Reynolds number on the variation of the concentration polarisation.

[1] Geraldes V., Semiao V., de Pinho M. N., (1998) *Industrial & Engineering Chemistry Research*, 37 (12): 4792-4800.
[2] Geraldes V., Semiao V., de Pinho M. N., (2000) *Engineering Computations*, 17 (2,3): 192-217.
[3] Geraldes V., Semiao V., de Pinho M. N., (2001) *Journal of Membrane Science*, 191: 109-128.
[4] Geraldes V., Semiao V., de Pinho M. N., (2002) *Chemical Engineering Science*, 57: 735-748.
[5] de Pinho M. N. , Semiao V., Geraldes V., (2002) *Journal of Membrane Science*, 206: 189-200.
[6] Geraldes V., Semiao V., de Pinho M. N., (2002) *Journal of Membrane Science*, 203: 87-102.
[7] Geraldes V., Semiao V., de Pinho M. N,, (2002) *Desalination*, 146: 187-194.
[8] Geraldes V., Semiao V., de Pinho M. N., (2004) *Computers and Structures*, 82 (17-19): 1561-1568.