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Numerical study of a hybrid membrane cell with semi and fully permeable membrane sub-sections

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Abstract

Hybrid membrane cells with up to 128 sections, each one comprising a fully and a semi-permeable membrane sub-section and, the limit case of a cell with an infinite number of membrane sections were studied by numerical methods. These hybrid cells separate a feed stream into two parts: a solvent stream which crosses the semi-permeable membranes and a concentrate stream which crosses the fully permeable membranes. The concentrate stream has a cleaning effect on the mass boundary layer over the semi-permeable membranes. The numerical results show that concentration polarization in hybrid cells is much lower than the polarization in conventional cells. Additionally, a highly concentrated solution is recovered. The cell with an infinite number of membrane sections (n) has the best performance: the lowest polarization and the highest concentration in the concentrate stream. As n increases to infinite, the concentration in the concentrate stream tends to the concentration over the semi-permeable membrane, i.e., to the maximum concentration inside the mass boundary layer. The number of membrane sections needed to achieve a performance similar to that of a cell with an infinite number of sections is very high, greater than 128. The velocity of the concentrate stream also plays an important role. As this velocity is increased (until an upper limit), the cleaning effect of the boundary layer intensifies but the purity of the concentrate stream decreases (dilution effect). An intermediate value for the velocity of the concentrate stream (between the lower and upper limit) should be used to optimize both effects.

Keywords: Membranes; Laminar flow; Mass transfer; Simulation; Computational fluid dynamics; Separations

1. Introduction

Cross-flow pressure-driven membrane processes such as reverse osmosis and ultrafiltration are useful to purify solvents, to concentrate solutions and to fractionate components. However, their efficiency is limited by the increase of solute concentration along the bulk of the retentate and by concentration polarization in the vicinity of the membrane. Solute concentration increases along the bulk because the solute is rejected by the membrane. The osmotic pressure in the bulk increases, and therefore the permeate velocity and the efficiency of the separation process decrease. Concentration polarization develops when the solute rejected by the membrane diffuses slowly away from the membrane and accumulates, mainly in the vicinity of the membrane surface, increasing the thickness of the mass boundary layer along the tangential direction. As the concentration at the membrane surface increases, the osmotic pressure increases and the permeate velocity, Sherwood number and membrane selectivity decrease.

Selectivity is an important problem in protein fractionation (van Reis et al., 1997; Cheang and Zydney, 2004; Ghosh, 2003). In this process, one of the proteins preferentially permeates the membrane, while the other is partially rejected. During polarization, the concentration of the rejected protein increases in the vicinity of the membrane and, because the permeation of this rejected protein increases with its concentration, the selectivity of the separation process decreases.

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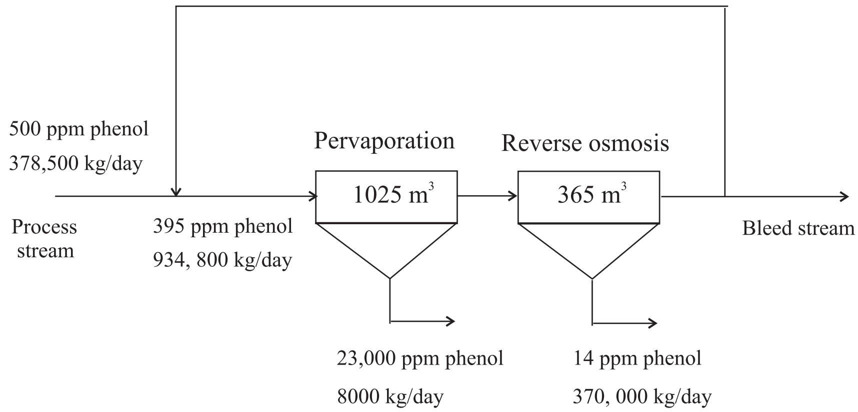

Fig. 1. Hybrid membrane system to recover phenol from wastewaters (Ray et al., 1991) comprising a pervaporation unit operation which recovers the solute (phenol) and a reverse osmosis unit operation which recovers the solvent (water).

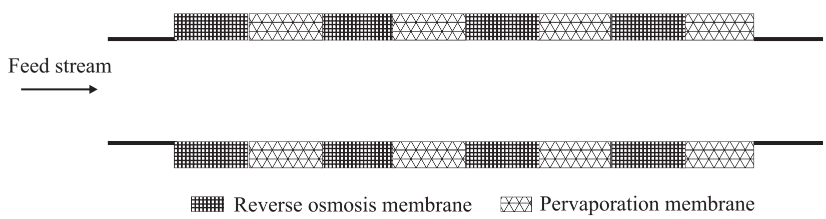

Fig. 2. Example of a hybrid membrane cell to separate volatile organic compounds (VOCs) from water. The cell comprises pervaporation membranes permeable to VOCs and reverse osmosis membranes permeable to water.

Since concentration polarization has so many undesirable effects, several mechanisms have been proposed to minimize it: turbulence promoters (Poyen et al., 1987), impinging jets (Miranda and Campos, 2000), backflushing (Kuberkar and Davis, 2001; Levesley and Hoare, 1999), Dean vortices (Chung et al., 1993) and pulse flow (Kennedy et al., 1974). Ironically, concentration polarization is a state of high solute/solvent separation. The solute concentration in the boundary layer is much higher than the solute concentration in the bulk of the retentate, and so an effective separation is achieved. However, some of the proposed mechanisms have the unintended consequence of mixing otherwise separated components.

Some authors have proposed solutions that take advantage of this effective state of separation. These solutions are based in the use of hybrid membrane systems (Fig. 1) or hybrid membrane cells (Fig. 2). Hybrid membrane systems combine two membrane unit operations. Usually, one unit operation performs a solvent removal operation and the other a solute removal operation. Hybrid membrane cells combine membranes with different properties, frequently alternating in series.

Binning (1961) was the first, as far as we know, to propose using a cell with two different membranes, each of which was permeable to one of the components of a binary mixture. In the cell proposed by Binning, the retentate concentration remains equal to the feed concentration. Shaw et al. (1972) analytically solved the flow and mass transport equations and concluded that in reverse osmosis productivity can increase by the use of intermediate non-rejecting membrane sections. Lee and Lightfoot (1974), Schubert and Todd (1980) and Mitrovic and Radovanovic (1984) proposed similar ideas. Lee and Lightfoot made some preliminary numerical simulations of an ultrafiltration cell with removal of fluid from the boundary layer. They found that the efficiency of this hybrid cell is higher than the efficiency of an analogous conventional cell. Schubert and Todd proposed the recovery of solute-rich fluid from the boundary layer at several locations along the membrane. Using numerical methods, Mitrovic and Radovanovic studied a cell with two different kinds of membranes alternating in series. Ray et al. (1991) studied hybrid membrane systems and showed that the use of complementary unit operations (solute removal and solvent removal unit operations) in the same system can improve separation efficiency because each unit can operate at optimized conditions. Nitsche and Zhuge (1995) studied anti-polarization dialysis, a process based in a hybrid cell with two membranes, a longitudinal dialysis membrane permeable to the solute and a transversal membrane impermeable to the solute but permeable to the solvent. Ideally, the polarization of the transversal membrane and the polarization of the longitudinal membrane should cancel each other (Nitsche and Zhuge, 1995).

This paper presents a numerical study of the separation of a solute from its solvent, in a hybrid cell with semi and fully permeable membrane sub-sections alternating in series.

The process takes advantage of the highly concentrated fluid in the polarized boundary layer to achieve a better separation