MODELING AND CALCULATION OF PRESSURE-DRIVEN MEMBRANE PROCESSES

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1. Introduction

There can be little doubt that, over the next few decades, there will be a very large increase in the human population of the earth, that per capita demand for water will increase, that water quality problems will require massive increases in investment, and that the price of oil and natural gas will increase sharply as resources become depleted. Against this background, pressure membrane processes for desalination and water treatment technology will become indispensable tools for the future of humanity.

Many factors will dictate the most favorable type of water treatment technology, but reduced capital costs and high efficiency are likely to be very important. In recent years, engineering and commercial interests have increasingly focused on sustainable technologies with greater energy efficiency and reduced environmental impact. Membrane technologies achieve markedly higher energy efficiencies than thermal distillation, and furthermore have seen significant developments in recent years. They are becoming increasingly attractive for a range of existing and potential applications. Current trends are likely to enhance the commercial potential and areas of proliferation for membrane processes. In addition to desalination of seawater, membrane processes offer elegant solutions to many ecological and technological problems. The new generation of membrane based operations, particularly in biotechnology, medicine and in oil processing, demands the development of an entirely new paradigm for design and calculation of membrane materials and processes.

The development of hybrid membrane processes for the treatment of biologically active materials, recovery of vaccines and antibiotics, purification of pharmaceuticals such as

interferon, isolation of cephalosporin from fermentation broth requires more comprehensive models and advanced methods of calculation. Complex inorganic membranes for the treatment of heated non-water media and aggressive fluids will require quantification and modeling of rheological anomalies and non-Newtonian behavior, along with temperature and concentration fields.

In recent years, membrane-based processes have achieved surprisingly high diffusion rate in some of these very specialized applications, particularly when compared to conventional processes. Analysts have suggested that the present market for RO modules and equipment, currently estimated at US $914 million will grow by 8 per cent a year to more than US$ 1.3 billion by the year 2003.

The viability of some membrane process applications have been hampered by the fact that many underlying models are based on unjustifiable simplifications and controversial assumptions within the framework of outdated methodological paradigms. This chapter is a contribution to the solution of such problems, and presents a set of linked transport submodels for solution, membrane and gel phase. The submodels are based on more physically defensible premises and are as comprehensive as possible at this stage without experimentation. The submodels are presented as core algorithms for calculation of pressure-driven membrane process.

2. General Framework and Formulation of the Problem

An algorithm of any membrane process is a set of linked submodels describing mass and energy fluxes in both liquid phases and across membrane. Any flux is proportional to driving force and inversely proportional to the overall resistance. The driving force for pressure-driven processes is pressure difference. Transport of mass and mechanical energy can be expresses as follows:

$$M(l) = \int_{z=0}^{z=H} u(z)c(z)\,dF \tag{1}$$

$$E(l) = \int_{z=0}^{z=H} \left(P + \frac{\rho u^2(z)}{2} \right) u(z)\,dF \tag{2}$$

These transport fluxes vary through the liquid and across the membrane. Main mass and energy transport fluxes are shown in Figure 1. The algorithm is based on the energy and mass balance equations. The balance equations have to be written for elementary control volume with constant mass and energy. The control volume being considered can be bounded by elementary parallelepiped, cylinder or fragment of intertubular channel. It is restricted by symmetry planes with no mass and energy transfer across them

The algorithm should comprise the submodels for calculation of resistance and driving forces. Unlike processes in impermeable channels in membrane operations, longitudinal and transverse fluxes of mass and energy vary from point to point along a semipermeable surface is caused by the fact that the resistance and driving force do not

remain constant owing to transmembrane flux and hydraulic losses. These aspects have to be accounted for by modeling. For this purpose we have to consider individual submodels describing behavior and transport in liquid phases (feed and permeate), transmembrane flow and transport through gel layer, and its behavior. The first step is to outline a set of physical premises and assumptions underlying these transport submodels.

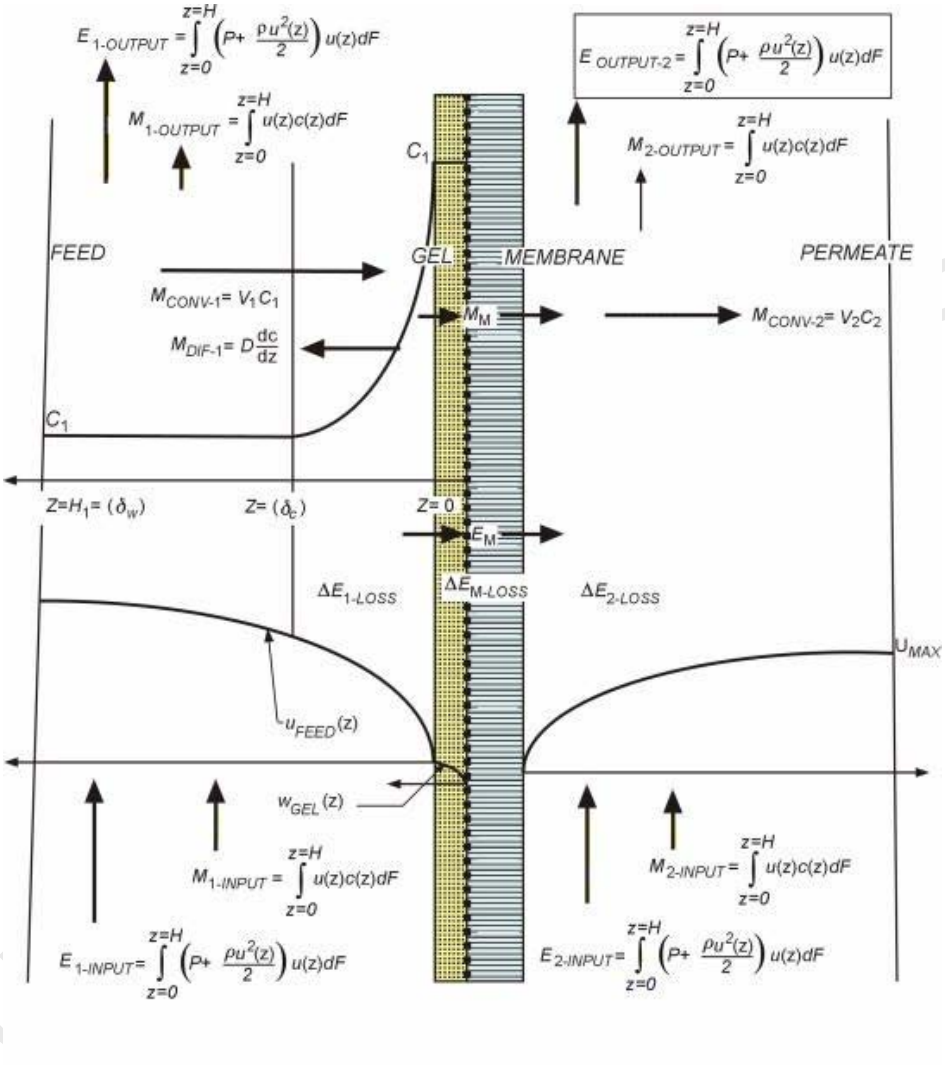

Figure 1. Schematic diagram of transport in membrane channel.

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Bibliography and Suggestions for further study

Agashichev S (1997) Modeling non-Newtonian behavior of gel layers at membrane surface in membrane filtration. *Desalination* 113, 235-246.

Agashichev S (1998) Modeling concentration polarisation in processes of ultrafiltration of non-Newtonian fluids. *Membrane Distillation, Osmotic Distillation and Membrane Contactors,* (Proceedings of Conference, Cetraro(CS), Italy, July 2-4, 1998, pp. 18-22.

Agashichev S (1998) Modeling concentration polarization phenomena for membrane channel with cylindrical geometry in an ultrafiltration process. *Desalination* 119, 159-168.

Agashichev S (1999) Modeling concentration polarization phenomena for shell-side flow in ultrafiltration process. *Separation Science and Technology* 43(2), 243-261

Agashichev S and Dmitriev E (1997) Stochastic modeling particle-size distribution in permeate and in concentrate on the stage of membrane pretreatment before reverse osmosis *Desalination* 110, (1997), pp.75-84.

Agashichev S and Falalejev D (1996) Modeling temperature polarization phenomena for longitudinal shell-side flow in membrane distillation process. *Desalination* 108, 99-103.

Agashichev S and Sivakov A (1993) Modeling and calculation of temperature and concentration polarization in the membrane distillation process (MD). *Desalination* 93 245 -258.

Bennett C O and Myers J E (1983) *Momentum, Heat, and Mass Transfer*, New York: McGraw-Hill Inc.

Berman A S (1953) Laminar flow in channels with porous walls. *Journal of Applied Physics*, 24, 1232-1235.

Blatt W F et al. (1970) Solute polarisation and cake formation in membrane ultrafiltration: causes, consequences and control techniques. Cake formation in membrane ultafiltration (ed. J E Flinn). New York: Plenum Press.

Brian P L (1965) Concentration polarisation in reverse osmosis desalination with variable flux and incomplete salt rejection. *Ind. Eng. Chem. Fund*. 4(4), 439- 445

Brodkey R S and Hershey H C (1988) *Transport Phenomena* (*A unified approach*). New York: McGraw-Hill Inc.

Davis R H (1992) Theory for cross flow microfiltration. In *Membrane Handbook* (eds W Ho and K. Sirkar). New York, VNR, 480-505.

Davis R H and Grant D C (1992) Theory for deadend microfiltration. In *Membrane Handbook* (eds W Ho and K Sirkar). New York, VNR, 461-479.

G. Owen, M. Bandi, J. A. Howell, S. J. Churchouse(1995), Economic assessment of membrane processes for water and waste water treatment Journal of Membrane Science, Volume 102, Pages 77-91

Gekas V (1986) *Terminology for Pressure Driven Membrane Operations*. European Society of Membrane Science and Technology.

Gerhart M, Gross R J and Hochstein J I (1992) *Fundamentals of Fluid Mechanics*. New York: Addison Wesley.

Ho W W S and Sirkar K K (1992) *Membrane Handbook*, New York: Van Nostrand.

J. I. Marriott, E. Sørensen, I. D. L. Bogle ,(2001),Detailed mathematical modelling of membrane modules,Computers & Chemical Engineering, Volume 25, Issues 4-6, Pages 693-700

J.I. Marriott, E. Sørensen, I.D.L. Bogle (2000),Detailed mathematical modelling of membrane modules ,Computer Aided Chemical Engineering, Volume 8, Pages 523-528

James Marriott1 and Eva Sørensen, (2003),A general approach to modelling membrane modules ,Chemical Engineering Science ,Volume 58, Issue 22, Pages 4975-4990

Kleinstreuer C and Paller M S (1983) Laminar dilute suspension flows in plate-and-frame ultra filtration units. *AIChE J*, 29, 4, 529-533

Koros W J, Ma Y H and Shmidzu T (1996) *Terminology for Membranes and Membrane Processes*, IUPAC Recommendations.

Krzysztof Karakulski, Marek Gryta, Antoni Morawski (2002),Membrane processes used for potable water quality improvement Desalination, Volume 145, Issues 1-3, Pages 315-319

Lundqvist R and Von Schalien R (1986) Mathematical modeling of colloidal ultrafiltration: A method for estimation ultrafiltration flux using experimental data and computer simulation. In: *Membrane and Membrane Processes* (eds E Drioly and M Nakagaki). London: Plenum Press, pp. 497-505.

Madsen R F (1977) Hyper filtration and ultra filtration in plate-and-frame systems. Amsterdam: Elsevier Scientific Publ. Co.

Mateus M and Cabral M S (1977) Modeling Membrane Filtration of Protein and Cell Suspensions in a Vortex Flow Filtration System. *AIChE J*. 41(4), 764-772

Oswald W and Auerbach R (1926) *Kolloid-Zeit*. 38, 261.

Perry's Chemical Engineers' Handbook (1984) 6th edn. New York: McGraw-Hill.

Porter M C (1977) The effect of fluid management on membrane filter throughput. In*: Proceedings of 2nd Pacif. Chem. Eng. Congr.*, New York, Vol. 2(4), pp. 975-982.

Rautenbach R and Albrecht R (1989) *Membrane Process*. New York: John Wiley and Sons Ltd.

S.A. Avlonitis, a, , M. Pappasa and K. Moutesidisa(2007) ,A unified model for the detailed investigation of membrane modules and RO plants performance ,Desalination Volume 203, Issues 1-3, Pages 218-228

Scherwood J K, Brian P L and Fisher R E (1965) Salt concentration at phase boundaries in desalination by reverse osmosis. *Ind Eng Chem Found* 4(2), 113-118.

Schlichting H (1974) *Grenzschicht-Theorie*, 5th edn. Karlsruhe: Verlag G. Braun.

Scott S (1995) *Handbook of Industrial Membranes*. Amsterdam: Elsevier Advanced Technology Ltd.

Sedov L I (1976) *Mechanics of Fluid*, Vols 1-2. Science Publ. (in Russian).

Sekino M (1995) Study of an analytical model for hollow fibre reverse osmosis module systems. *Desalination* 100, 85-97.

Valeri V.Ugrozov and Ljubov I. Kataeva(2004), Mathematical modeling of membrane distiller with liquid gap, Desalination Volume 168, Pages 347-353

Yuan S W and Finkelstein A B (1956) Laminar pipe flow with injection and suction through a porous wall. *Transaction ASME*, 78(4), 719-724.