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A predictive model for spiral wound reverse osmosis membrane modules: The effect of winding geometry and accurate geometric details

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ABSTRACT

A new one-dimensional predictive model for spiral wound modules (SWMs) applied to reverse osmosis membrane systems is developed by incorporating a detailed description of the geometric features of SWMs and considering flow in two directions. The proposed model is found to capture existing experimental data well, with similar accuracy to the widely-used plate model in which the SWM is assumed to consist of multiple thin rectangular channels. However, physical parameters that should in principle be model-independent, such as membrane permeability, are found to differ significantly depending on which model is used, when the same data sets are used for parameter estimation. Conversely, when using the same physical parameter values in both models, the water recovery predicted by the plate-like model is 12–20% higher than that predicted by the spiral model. This discrepancy is due to differences in the description of geometric features, in particular the active membrane area and the variable channel heights through the module, which impact on predicted performance and energy consumption. A number of design variables – the number of membrane leaves, membrane dimensions, centre pipe radius and the height of feed and permeate channels – are varied and their effects on performance, energy consumption and calculated module size are analysed. The proposed spiral model provides valuable insights into the effects of complex geometry on the performance of the SWM as well as of the overall system, at a low computational cost.

1. Introduction

Reverse osmosis (RO) processes have been widely used in many applications, especially for producing nearly pure water from seawater in desalination plants, and have seen a dramatic increase in their market share in recent years (Elimelech and Phillip, 2011; Fritzmann et al., 2007; Ghaffour et al., 2013; Greenlee et al., 2009; Kim et al., 2009; Malaeb and Ayoub, 2011; Semiat, 2008). In an RO process external hydraulic pressure that exceeds the osmotic pressure difference between two solutions is applied to the side where the more concentrated solution is placed. As a result, water passes through a semi-permeable RO membrane at a rate that is proportional to the difference between the external pressure gradient and the osmotic pressure gradient, while salts dissolved in concentrated solution are rejected. Using RO membrane systems, seawater can be separated into pure water and concentrated brine containing the rejected salts.

RO membrane modules are commercially manufactured for their use in large scale plants and spiral wound modules (SWMs) are most widely adopted among commercially available RO membrane modules (Schwinge et al., 2004). In SWMs, several sheets of RO membranes and feed and permeate spacers are alternately stacked and wrapped around a perforated centre pipe, forming separate feed and permeate channels. Due to the wrapping of membranes and spacers, the module has a complex geometry that can be difficult to capture in mathematical models.

Models of SWMs have been reported by many authors in order to predict performance and energy consumption, which have a direct influence on the overall RO process (Avlonitis et al., 1991, 1993; Boudinar et al., 1992; Dickson et al., 1992; Evangelista and Jonsson, 1988; Geraldes et al., 2005; Riverol and Pilipovik, 2005; Schock and Miquel, 1987; Senthilmurugan et al., 2005; Taniguchi, 1978;

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Nomenclature

Symbols

A	Water permeability constant [m^3/m^2 s Pa]
A_c	Cross-sectional area of feed channel [m^2]
$A_{c,p}$	Cross-sectional area of permeate channel [m^2]
$A_{c,SWM}$	Total cross-sectional area of feed channel at entrance [m^2]
A_t	Trans-membrane area [m^2]
A_{tot}	Total membrane area [m^2]
B	Salt permeability constant [m/s]
c	Concentration [kg/m^3]
d_1	Constant used in parametric equations
d_{2k}	Constant used in parametric equations
d_{3j}	Constant used in parametric equations
d_h	Hydraulic diameter [m]
E_{sp}	Specific energy consumption [kWh/m^3]
F	Objective function
H	Spacer thickness [m]
H_k	Parameter for curve k [m]
h	Channel height [m]
j	Index of membrane leaves
J_w	Water flux [m^3/m^2 s]
$J_{w,eff}$	Effective water flux [m^3/m^2 s]
J_s	Salt flux [kg/m^2 s]
k_{sp}	Frictional coefficient [−]
L	Active length of membrane leaves [m]
L_g	Glue line thickness in length direction [m]
L_i	Initial length of membrane leaves [m]
m	Number of variables
N_{leaf}	Number of membrane leaves
n	Number of data
P	Pressure [Pa]
P_{atm}	Atmospheric pressure [Pa]
P_{drop}	Pressure drop in feed channel [Pa]
$P_{p,in}$	Permeate pressure at the closed end [Pa]
Q	Volumetric flowrate [m^3/s]
R	Gas constant [m^3 Pa/K kmol]
R_w	Water recovery [%]
r_c	Radius of centre pipe [m]
r_k	Radial position of curve k [m]
r_{oc}	Radius of outer cover [m]
s	Arc length [m]
$\bar{s}$	Flow path length of permeate stream
u	Flow velocity [m/s]
V	Control volume [m^3]
W	Active width of membrane leaves [m]
W_g	Glue line thickness in width direction [m]
W_i	Initial width of membrane leaves [m]
w^j	Weighting factor of j-th variable
x	Permeate flow direction in cartesian coordinate system for unwound membrane [m]
x_{kj}	x-coordinate for spiral curve kj in cartesian coordinate system [m]
x_c	x-coordinate for centre pipe curve in cartesian coordinate system [m]
x_{oc}	x-coordinate for outer cover curve in cartesian coordinate system [m]
y	Channel height direction in cartesian coordinate system for unwound membrane [m]
y_{kj}	y-coordinate for spiral curve kj in cartesian coordinate system [m]
y_c	y-coordinate for centre pipe curve in cartesian coordinate system [m]
y_{oc}	y-coordinate for outer cover curve in cartesian coordinate system [m]
$y^{i,j}$	i-th measured values of j-variable
$\hat{y}^{i,j}$	i-th calculated values of j-variable
z	Feed flow direction in cartesian coordinate system for unwound membrane [m]

Greek letters

μ	Dynamic viscosity [Pa s]
ε	Small gap between outermost layer and outer cover [m]