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Reverse osmosis desalination modules containing corrugated membranes – Computational study

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ABSTRACT

Computational fluid dynamics simulation was carried out for three-dimensional desalination modules containing triangular and square ribs attached to the membrane surface. The solution-diffusion membrane transport model was applied along the surface of the corrugated membrane. The membrane flux model which couples the water permeation rate with local salt concentration impose a selective removal of components in the feed channel. The local water flux, salt concentration, wall shear stress, and Sherwood number were monitored over the surface of membranes to determine effects of eddy promoter corrugations on mitigation of concentration polarization and the total water flux. Simulations are conducted using a laminar model for Reynolds number of 100 and k-ω SST turbulence model for Reynolds number of 400 and 1000. Mathematical model and numerical methods employed are validated by comparing predictions against measurements reported earlier. Predicted results agree quantitatively and qualitatively with previous experimental results for membranes with semi-circular cross-sectioned ribs. The results show that corrugated membranes especially triangular chevrons enhance membrane performance profoundly at all flow rates. Water permeation rate is increased, concentration polarization is alleviated, and the potential fouling in the module is reduced by introducing corrugated membranes.

1. Introduction

Reverse Osmosis (RO) is one of many desalination processes used to produce freshwater from brackish water. With the application of pressure greater than osmotic pressure, a solvent (water) from a high solute (salt) concentration region passes to a low solute concentration region through a semipermeable membrane. Selective mass transport through membranes inherently causes concentration polarization. Concentration polarization reduces the driving pressure for water permeate by increasing the osmotic pressure. It also causes salt leakage and increases the risk of potential fouling and scaling. Enhanced momentum mixing in the module can improve membrane flux performance and can aid in alleviating concentration polarization. Comprehensive reviews of the topic can be found in Ref [1–4]. Corrugated membranes and spacers are commonly used as momentum mixing promoters in spiral wound membrane modules. This study considers reverse osmosis desalination modules consisting of ribs of different shapes imprinted over the surface of the membranes. Computational fluid dynamics simulations are conducted to characterize flow and mass transport characteristics and membrane performance by employing the solution diffusion membrane flux model. To the best knowledge of authors, three-dimensional computational study of desalination module containing corrugated membranes has not been conducted with the coupled mass transport equations and membrane flux models.

Recently, several researchers [5–10] have fabricated corrugated membranes with various patterns over the surface of membranes. Scott et al. [5] modified commercial membrane by mechanical pressing to form a corrugated membrane. The corrugated membrane was then used to filter water-in-oil emulsion. Scott and his coworkers reported up to 160% increase of the membrane flux and up to 88% of energy savings when compared to a module with flat membranes. Another membrane alteration was done by Maruf and his team [6,7]. They used silicon (Si) mold with sub-micron patterns to imprint the patterns on an ultrafiltration membrane surface [6] and on a thin film composite membrane for reverse osmosis [7]. These studies concluded that the membranes with patterns became more fouling resistant than flat membranes. Kharraz et al. [8] fabricated polyvinylidenfluoride (PVDF) corrugated membranes for water desalination by membrane distillation and performed experimental testing and surface characterization. Kharraz et al. documented that corrugated membranes maintained better water flux level and antifouling than flat membranes. Maruf et al. [6,7] and

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Nomenclatures

a_1	turbulence model parameters
A	membrane permeability [m/s Pa]
c	concentration [kg/m^3]
c_0	inlet concentration [kg/m^3]
c_b	bulk concentration [kg/m^3]
c_p	production side membrane concentration [kg/m^3]
c_w	feed side membrane concentration [kg/m^3]
CP	coefficient of performance
D	diffusion coefficient [m^2/s]
f	pressure coefficient
F_1, F_2	blending functions
h	height of the channel
h_m	mass transfer coefficient [m/s]
k	turbulent kinetic energy [J/kg]
Δp	transmembrane pressure difference [Pa]
Re	Reynolds number
Sc	Schmidt number
Sh	Sherwood number
$u_i\,(u, v, w)$	velocity vector [m/s]
U_{ave}	average inlet velocity [m/s]
v_w	local water flux [m/s]
$x_i\,(x, y, z)$	position vector [m]

Greek letters

β, β^*	turbulence model parameters
γ	turbulence model parameters
κ	osmotic coefficient [kPa m^3/kg]
μ	dynamic viscosity [Pa s]
μ_t	eddy viscosity [Pa s]
ν	kinematic viscosity [m^2/s]
ν_t	kinematic eddy viscosity [m^2/s]
ω	specific dissipation rate [1/s]
$\Delta\pi$	osmatic pressure [Pa]
ρ	density [kg/m^3]
σ_{k1}	turbulence model parameters
$\sigma_\omega, \sigma_{\omega 2}$	turbulence model parameters
τ_w	normalized wall shear stress

Subscripts

i and j	index notation
w	properties along the surface of membrane

Kharraz et al. [8] anticipated that patterns on the membrane surface promote more mass and momentum mixing which enhances the membrane performance. Ho et al. [9] and Altman et al. [10] have studied numerically and experimentally the water desalination by reverse osmosis membranes with three-dimensional (3D) printed patterns. Computational study conducted by these investigators does not consider membrane flux model imposed on the surface of these corrugated membranes. The patterns were created by a 3D printer using UV-curable epoxy, and the patterns laid on the RO membrane were a chevron-like shape in different configurations. The patterns on the membrane caused a chaotic flow in the feed channel [9]. The membrane with patterns had less bio-fouling than the membrane with spacers, but the membrane with spacers had greater water flux [10]. Kang and Chang [11] performed numerical simulations and flow visualizations to study flow and mass transfer in a channel with ribs attached to electrodialyzer membranes in different configurations. They observed that the flow transition from laminar to turbulent regime occurs at Reynolds number above 300 with Reynolds number is defined based on the channel height and the average bulk velocity. They reported that mass transfer was enhanced considerably when ribs were attached to membranes.

In spiral wound modules, spacers can also be used as a mixing promoter. Spacers maintain a gap between membranes and generate momentum mixing in the feed channel. However, the presence of spacers can increase pressure drops in the feed channel, and as a result the cost of water production increases [3]. Several investigators study effects of spacers on the performance of desalination modules. Geraldes et al. [12] have studied effects of the ladder-type spacers on nanofiltration in spiral wound modules. Fimbres- Weihs and Wiley [13] have studied mass transfer enhancement in modules containing spacer filaments. Karode and Kumar [14] have carried out computational fluid dynamics simulations in desalination modules filled with net type of spacers. Their study revealed that ratio of filament diameter to inner-filament distance is a key parameter to obtain low-pressure drop and high wall shear stress resulting in enhanced mass transfer. Shakaib et al. [15] and Srivathsan et al. [16] employed numerical simulations to predict flow field and concentration distribution in the feed channel containing spacers arranged at various distances and orientations. They showed that a spacer geometry has a strong influence on the local distribution of shear stress and mass transfer coefficient. Anqi and his co-workers [17,18] numerically characterized the flow field and concentration distribution in a spacer filled RO desalination membrane for various flow rates. They applied the solution-diffusion model that couples the local salt concentration, the suction rate and the pressure on the membrane surface. They observed a correlation between high shear stress and low salt concentration regions and concluded that spacers presumably mitigates the concentration polarization and improves membrane performance significantly. Koutsou and his co-workers [19,20] conducted experimental measurements and direct numerical simulations of the flow and mass transfer in desalination modules containing spacers. Their study concluded that high values of mass transfer coefficient and low fouling regions coincide with areas of high wall shear stress along the membrane surface. They also stated that the high fouling zones occur at the areas of high salt concentrations polarization along the membrane surface. Neal et al. [21] studied particle depositions in spacer-filled channels. Their experiment proved a direct relation between particle deposition characteristics and the spacer geometry. Turbulent flow structures help to alleviate the salt concentration polarization near the membrane surface. The reduction of salt concentration reduces the osmotic pressure in the vicinity of the membrane in the feed side, and, therefore, the pure water production improves. Mahdavifar et al. [22] employed direct numerical simulations to study the flow in a channel with spacers. These investigators concluded that spacers promote good mixing in the feed channel at low flow rates.

The present work conducts computational fluid dynamics simulations to characterize flow and concentration fields in modules containing in-phase chevrons on both top and bottom membrane and to assess the effect of corrugation on the membrane flux performance, the shear stress and the concentration polarization characteristics. The laminar flow model is employed for Reynolds number of 100, while k-ω Shear Stress Transport (SST) turbulence model is used for Reynolds number of 400 and 1000. The solution-diffusion model based membrane flux model is applied and the water permeate loss is taken into account to mimic real membrane module operating conditions.

2. Mathematical model

Navier-Stokes equations are used to characterize the fluid motion of incompressible fluids. Conservation of mass yields