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Concentration polarization and permeate flux variation in a vibration enhanced reverse osmosis membrane module

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ABSTRACT

The performance of a vibration enhanced reverse osmosis membrane module for desalination of artificial seawater was investigated with computational fluid dynamics (CFD) simulations and experiments. The computational model couples fluid dynamics with solutes transport inside the full length domain containing 'zigzag' spacers using a two dimensional, transient Large Eddy Simulation turbulence model. Both the local concentration dependent solute properties and variation of permeate flux over the membrane surface were predicted with the model. Membrane local permeate flux, concentration polarization, shear rate, and mass transfer were also calculated. The results suggest concentration polarization in the seawater desalination process could be reduced by imposing vibration on the reverse osmosis membrane. It was determined that the higher the vibration frequency the higher the membrane permeate flux while keeping the vibration amplitude constant. The CFD simulation predictions are validated against experimental data of permeate fluxes with good agreement.

1. Introduction

High pressure seawater reverse osmosis (RO) is one of the most economic approaches for desalination. One challenge of RO membrane system is the concentration polarization phenomenon caused by the accumulation of rejected solutes and particles on the membrane surface. Concentration polarization will reduce permeate flux through the membrane and accelerate the membrane fouling, which limits the membrane lifetime [1]. Therefore, accurate predictions of the solute local concentration profile, and concentration polarization improvement are highly desired for improved design and operation of membrane desalination systems.

As mentioned in the review by Ghidossi et al. [2], computational fluid dynamics (CFD) is becoming more important in RO membrane science since it can provide more detailed flow and solute distribution information, especially when combining CFD simulation with laboratory membrane module experiments.

Experiments with ladder-type, spacer-filled rectangular channels with a tracer injection flow visualization technique were performed by Geraldes et al. [3] to study the effects of spacer parameters on membrane performance. The flow visualization and friction factor measurements showed that critical Reynolds numbers increase with the decrease of the distance between spacers.

Fimbres-Weihs et al. [4] studied transient unsteady flows inside two dimensional spacer-filled channels using the CFD method. Unsteady flow patterns were observed inside the feed channels at Reynolds number of 841 and 1683. Vortices formed and grew behind the feed spacer moving downstream with the bulk flow. The regions where the fluid flowed near the membrane wall contained both high mass transfer rate and high shear rate.

Concentration polarization profiles for three single salt solutions of $NaCl$, $CaCl_2$ and Na_2SO_4 in a rectangular RO and laboratory plate-and-frame RO membrane channel were numerically investigated by Lyster and Cohen [5]. They proved the importance of coupling fluid dynamics and mass transfer governing equations and accounting for permeate flux variability along the membrane surface for studying membrane concentration polarization profiles.

High shear rate at the membrane surface to reduce solute/particle deposition is known to be an effective way to reduce concentration polarization and increase the permeate flux in cross-flow membrane filtration [6–9]. Imposing motion of the membrane is one way to increase the shear rate at the membrane surface. Yeh and Cheng [10] used boundary layer theory to analyze membrane surface slip effect on the permeate flux in ultra-filtration. They found that the mass-transfer rate as well as permeate flux increase with the increase of the membrane slip velocity, which reduces the concentration polarization. A similar conclusion was also found by Chellam et al. [11] according to their 2D simulation of a channel bounded by one porous membrane

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wall boundary subject to uniform suction.

The vibratory shear enhanced filtration process (VSEP) [12] is a commercial unit that relies on rapid membrane motion to induce large shear rate. The VSEP system can be treated as a disk-shaped desalination cell attached to a central shaft, utilizing high frequency torsional vibration of membrane to impose membrane motion. AI Akoum et al. [13] performed experiments to investigate the performance of VSEP module in yeast microfiltration (MF) and bovine albumin ultrafiltration (UF). They found that for both yeast MF and bovine albumin UF, the higher the membrane shear rate, the higher the permeate flux with torsional vibration frequency in the range of 56 Hz to 61 Hz. Experimental research investigated by Shi and Benjamin [14] indicated that inorganic fouling can be reduced by high shear rate at the membrane surface imposed by the torsional vibration of VSEP system. A study proposed by Shi and Benjamin [15] revealed that an increase in vibration amplitude will decrease the membrane fouling and increase the rejection of most solutes. Varying both vibration frequency and amplitude showed that membrane fouling rate was almost invariant as long as the averaged shear rate is the same. However, the vibration amplitude of points near the center of shaking will have less effective shaking amplitude for the torsional vibration utilized in the VSEP system. This may not fully utilize the vibration benefit on salt concentration polarization reduction and fouling mitigation.

In this study, a novel vibration enhanced desalination technique was proposed to address the RO membrane concentration polarization problem, with the aim of increasing membrane permeate flux and reducing membrane salt concentration. In this technique, a RO membrane desalination cell is driven by linear actuators to impose axial rapid membrane vibration and large membrane surface shear rates. Fifteen cases for different vibration and flow conditions were first performed in the vibration enhanced reverse osmosis membrane desalination setup to experimentally study the effect of vibration on RO membranes for seawater desalination. Detailed hydrodynamics were then analyzed using transient CFD simulation consisting of the fully coupled fluid dynamics and solute transportation governing equations performed for the 2D spacer-filled, full length vibration membrane channel. Finally, the simulation results were validated by the corresponding experimental observations.

2. Experimental work

2.1. Simulated seawater feed solution composition and membranes

Distilled water was used to prepare the artificial seawater feed solution. The composition of feed solution is listed in Table 1. All chemicals used in feed water preparation were reagent grade and purchased from Fisher Scientific.

The membrane used in all tests had 20 cm length × 3 cm width, yielding an effective membrane area of 60 cm^2. Specifications for the membrane are summarized in Table 2 [17].

2.2. Vibratory RO membrane test cell set up

Fig. 1 shows the vibratory RO membrane cell module, which is employed for all experiments. This membrane cell module has two separate parts. The upper part contains the high pressure feed channel, a feed water inlet port and a retentate outlet port. The height of the feed channel is 0.78 mm and the feed spacer is placed inside the feed channel. The feed spacer used in experiments is cut from commercial RO membrane unit. Square rubber O-rings are used for sealing. The bottom part contains the permeate channel and two permeate outlet ports. The permeate carrier is placed inside the permeate channel which collects and transports permeate water to permeate ports.

Table 1
Feed water composition.

Chemical	mol/L
$NaCl$	0.4187
$MgSO_4$	0.0503
$CaCl_2$	0.0342
Na_2SO_4	0.0172

Table 2
Specification of the membrane.

Membrane	SWC6 MAX
Vendor	Hydranautics
Material	Composite polyamide
Permeate flow[a]	7.2 lpd
Salt rejection	99.8%
pH range, continuous	2–11
Max Cl_2 concentration	0.1 ppm
Max temperature	318 K

[a] At 55 bar applied pressure.

The RO desalination cell is fixed on two shafts and supported by four linear bearings in Fig. 2. A linear actuator (LinMot Inc., P01-48 × 360F/60 × 210) is controlled by a laptop-based program and is used to vibrate the cell at desired amplitude and frequency. For all vibration cases, vibration amplitude is fixed at 1.2 mm while vibration frequency varies from 20 Hz to 50 Hz.

Fig. 3 shows a hydraulic circuit diagram of the test installation. The stainless steel feed tank has a volume of 22.7 L and serves as a supply for the stainless steel diaphragm pump (Hydra-Cell, M03BABTHFECA) which pressurizes the feed solution. The pulsation dampener (CAT, 6028) is used to absorb the feed flow pressure fluctuations. The inlet pressure and flow rate are measured by a digital pressure transducer (Omega, PX309-1KGV) and in-line flow meter just upstream of the desalination cell. The pressure relief valve and regulating valve are used to adjust the cell pressure and feed flow rate, respectively. The retentate flow goes through the regulating valve to reduce pressure to atmosphere and goes back to the feed tank. The permeate flow is collected and measured at the desalination cell side. Permeate flow is poured back to the feed tank after measuring in order to keep the feed water salinity constant. The concentration of the feed water and permeate water was measured by a conductivity meter (Hana Instruments Inc., HI98192), which has an EC accuracy of 0.01 S/cm.

2.3. Experiment procedure

A new membrane was used for each experiment and was first compacted using distilled water at an operating pressure of 55 bar for at least 4 h until a stable baseline permeate flux was obtained.

Non-vibration membrane cases with three different inlet flow rate were performed in order to establish the benchmark data to compare with the vibration test cases. Vibration values, permeate flux, permeate salinity, feed pressure and feed water temperature were recorded during each vibration membrane test, while keeping the feed flow rate and feed pressure constant.

A feed pressure of 55 bar was employed for all tests and three different feed flow rates were utilized: 0.3785 lpm, 0.5678 lpm, and 0.7570 lpm. These feed flow rates produced three different inlet Reynolds numbers: $Re = 344$, 516 and 688, respectively. The feed solution temperature was kept in the temperature range of 25 ± 1 °C and measured by a J-type thermocouple with 0.1 °C accuracy.

3. Theory and CFD numerical simulations

3.1. Governing equations

The hydrodynamics of the transient two-dimensional flow inside a