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Numerical analysis of hollow fiber membranes for desalination

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HIGHLIGHTS

- Numerical characterization of hollow fiber membrane for desalination
- Reverse osmosis membranes are arranged in an inline and a staggered geometry.
- Spatial and temporal characteristics of the flow in the bank of fibers are examined.
- Hollow fiber membranes in the staggered geometry perform better.

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ABSTRACT

Water desalination by reverse osmosis hollow fiber membrane has been widely used to produce fresh water. This work numerically characterizes flux performance of the membrane, concentration polarization and potential fouling sites in the reverse osmosis desalination module containing hollow fiber membranes arranged in an inline and staggered configuration. Steady k-ω SST turbulence model is utilized to study membrane performance. An accurate membrane flux model, the solution-diffusion model, is employed. Hollow fiber membrane surface is treated as a functional boundary where the rate of water permeation is coupled with local concentration along the membrane surface. The rate of water permeation increases and concentration polarization decreases as the feed flow rate is increased. Hollow fiber membranes in the staggered geometry perform better than those in the inline geometry. It is proven by the present study that desalination modules containing hollow fiber membranes should be designed and optimized by careful consideration of their configurations. It is demonstrated here that flows in the hollow fiber bank becomes strongly time dependent at high flow rates and that transient effects could profoundly influence hollow fiber membrane flux performance and characterization of concentration polarization.

1. Introduction

Reverse osmosis (RO) desalination is a common process to produce fresh water. The process requires high pressure in a feed channel of the separation module. The applied pressure has to be larger than the osmotic pressure of the dissolved salt. The selective hollow fiber membrane passes water and rejects dissolved salt. The rejected salt can accumulate near the surface of the membrane and can result in a concentration polarization. It is well-known that the salt concentration polarization at RO membrane surface adversely affects the pure water production. It has been documented that the concentration polarization reduction at the membrane surface increases membrane life time [1,2]. It is reported by the present authors that the concentration polarization and the fouling buildup can be mitigated by promotion of the momentum mixing in the feed channel in desalination modules [3–5]. For design and optimization of these separation modules the membrane flux performance, concentration polarization and fouling-buildup/scaling need to be characterized. The present authors documented that the momentum mixing in the feed channel help improves the membrane flux performance in both gas separation and desalination modules [3–9].

Several investigators, including present authors, [3–7,10–12] have studied velocity and concentration field in the feed channel to characterize membrane performance in spiral wound membrane modules. Shakaib et al. [10] conducted three dimensional flow simulations in a feed channel that contains spacers. They reported that the membrane performance is influenced by momentum mixing in the feed channel

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Nomenclature

(u,v)	components of velocity [m/s]
h_m	mass transfer coefficient [m/s]
C_D	drag coefficient
F_1,F_2	blending functions
L	length of hollow fiber membrane bank [m]
U_{in}	average inlet velocity [m/s]
S	spacing [m]
a_1	turbulent model parameter
C_0	inlet concentration [kg/m^3]
C_b	bulk concentration [kg/m^3]
C_p	production concentration [kg/m^3]
C_w	membrane salt concentration [kg/m^3]
f	pressure coefficient
f_x	drag force [N]
f_m	particle density distribution function
Δp	transmembrane pressure difference [Pa]
$\vec{x}$	position vector
v_w	water flux [m/s]
H	height [m]
A	membrane permeability [m/s Pa]
A_m	area of the hollow fiber membrane projected normal to the flow [m^2]
D	diffusion coefficient [m^2/s]
d	hydraulic diameter [m]
Re	Reynolds number, $Re = dU_{in}/\nu$
Sh	Sherwood number, $Sh = dh_m/D$
Sc	Schmidt number, $Sc = \nu/D$
Δp_p	pressure drop across the bank [Pa]
k	turbulent kinetic energy [J/kg]
p	pressure [Pa]
CP	coefficient of performance
e_i	discrete lattice velocity set
$\vec{u}$	flow velocity vector
δt	lattice time

Greek letters

μ_t	eddy viscosity [Pa s]
ν_t	kinematic eddy viscosity [m^2/s]
σ_{k1}	turbulent model parameter
$\sigma_\omega,\sigma_{\omega 2}$	turbulent model parameters
β,β^*	turbulent model parameters
γ	turbulent model parameter
$\Delta\pi$	osmotic pressure [Pa]
τ	dimensionless time
μ	dynamic viscosity [Pa s]
ν	kinematic viscosity [m^2/s]
ρ	density [kg/m^3]
ω	specific dissipation rate [1/s]
$\boldsymbol{\kappa}$	osmotic coefficient [kPa m^3/kg]
θ	angle [°]
τ_w	Normalized wall shear stress

Subscripts

i and j	index notation
w	properties along the membrane surface

bounded by the impermeable walls. Geraldes et al. [11] have numerically studied velocity and concentration field in a feed channel of a RO desalination module. The water flux through the membrane was determined by implementing pre-determined permeate velocity along the membrane surface. Geraldes et al. proved that the placement of spacers closer to the membrane surface enhances membrane performance. Ma and Song [12] employed a membrane flux model that couples salt concentration and water permeate along the membrane surface in a spiral wound membrane module. Ma and Song demonstrated that membrane flux performance is influenced by the arrangement of spacers.

Experimental and numerical characterization of hollow fiber membranes has been documented [8,9,13–21]. Recently, Alrehili et al. [8] characterized membrane performance in a gas separation module containing an array of hollow fiber membranes. Velocity and concentration profiles over a bank of hollow fiber membrane are calculated for various flow rates. Alrehili et al. [8] showed that the arrangement of the hollow fiber membranes in a gas separation module has profound influence on the membrane performance. Alkhamis et al. [9] studied the process of separating carbon dioxide from methane in a membrane module containing porous medium and selective membranes. Marcovecchio et al. [13] characterized concentration polarization in a hollow fiber membrane module for reverse osmosis desalination process by conducting computational fluid dynamics simulations. Marcovecchio et al. concluded that the performance of the desalination using hollow fiber membranes is strongly dependent on the concentration and pressure distribution in the feed channel. Ghidossi et al. [14] examined the pressure drop and membrane characteristics for various operating conditions in a hollow fiber membrane module. High performance hollow fiber membranes similar to those considered in the present study have been fabricated and tested in laboratories. Sukitpaneenit and Chung [15] fabricated high performance thin-film composite forward osmosis hollow fiber membranes. They reported that the water flux increases with an increase in draw solution concentration since a larger effective osmotic pressure difference provides a greater driving force. Chou et al. [16] designed and fabricated pressure retarded osmosis hollow fiber membrane. Chou and his co-workers have built thin-film composite hollow fiber membrane with high permeability and high rejection rate.

Experimental and computational studies were conducted for modules containing a bank of hollow fiber membranes for humidification and dehumidification processes [17,18,21,22]. Huang and his co-workers [17,18] reported that the membrane performance is improved by the proposed elliptical hollow fiber membrane. Zhang et al. [21] conducted experiments to study heat and mass transfer in a module containing a bundle of hollow fiber membranes with different arrangements. They concluded that the flow inside the hollow fiber bank is turbulent and that heat and mass transfer performance of module containing hollow fibers in a staggered arrangement is better than that containing inline arrangements of fibers. Experimental study by Huang et al. [20] revealed that the staggered configurations with high packing fraction perform better heat and mass transfer. Teoh at al. [22] have conducted experimental study to investigate the effect of various hollow fiber membrane geometries on the performance of the distillation process. Teoh et al. documented that the module with twisted and braided hollow fibers design provides permeate flux that is 35% greater compared to other designs considered.

Lattice Boltzmann method (LBM) is relatively new and innovative method that employs kinetic theory to simulate fluid flows [23]. The method is essentially equivalent to a direct numerical solution (DNS). The discretized equations by the lattice Boltzmann method can easily be parallelized; that makes the method to be an effective computational tool. The method is very versatile and it can be used to simulate complex flow systems [24]. The present study employs LBM to study two dimensional transient flows in a channel containing arrays of impermeable cylinders. The objectives of utilizing lattice Boltzmann method are two folds: (1) to validate the turbulence model employed here and (2) to characterize temporal characteristics of the flow inside the hollow fiber bank.

The present work examines the velocity and concentration fields to evaluate the membrane flux performance, concentration polarization