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Twisted hollow fiber membrane modules for reverse osmosis-driven desalination

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ABSTRACT

We show how a simple design adaptation creates desirable flow structures that dramatically enhance performance in hollow fiber membrane (HFM) water desalination modules using computational fluid dynamics (CFD) simulations. Conventional HFM desalination modules encase thousands of co-axially aligned HFMs in a mutually parallel flow of brackish water. HFMs are subject to a phenomenon called concentration polarization (CP), which leads to fouling and will eventually prevent clean water production. We found that the twisted HFM module mitigates CP effects and increases transmembrane permeate flux by 5–9% for three flow rates considered. Twisted HFM bundles induce swirling flow structures inside desalination modules that increase momentum mixing throughout. Frictional energy losses and increased pumping power associated with this subtle design alteration are small relative to projected gains in clean water production. We predict system performance increases about 70% for the twisted modules herein considered, and there are in principle no additional required components associated with this geometry adaptation. With our findings, we identify how the twisted module design induces desirable flow structures that increase membrane separation performance by mitigating CP effects and increasing HFM efficacy.

1. Introduction

When pressure is applied to a brackish solution that is larger than its osmotic pressure, clean water is removed from the brackish solution and passes through a semi-permeable HFM so that dissolved salts and other impurities are left behind. This process is called reverse osmosis (RO), and it is a dominant method for water desalination because it requires little energy consumption relative to other thermal distillation methods. During clean water production, the salts, organic, and inorganic molecules left behind tend to congregate along HFM surfaces if the surrounding flow is unable to carry them away, which makes the local solute concentration in these regions very high relative to the bulk flow. As operation continues, particle accumulation along membrane surfaces turns to fouling and scaling, which will eventually prevent clean water production altogether. In that case, the operation must be interrupted to flush away the deposited crusts, or they must be removed by other physical means prior to continuing clean water production.

Regions along HFM surfaces where the local salt concentration is large relative to the bulk are said to exhibit concentration polarization (CP), which is a precursor to fouling. Herein, we focus on CP mitigation in order to abate losses due to fouling. One way to mitigate CP is by increasing the momentum mixing in the module, which increases mass transport of accumulated retentate along membrane surfaces back into the bulk flow and disrupts local concentration fields along and near to HFM surfaces [1]. Increased momentum mixing appears to be an effective method of CP mitigation because of the strong correlation between high wall shear stress and low CP, independent of membrane type [2–7]. The importance of accurately representing local salt concentrations in numerical studies is well exemplified by Marcovecchio et al. [8], who presented a model to predict the permeation performance in HFM desalination modules by means of appropriate flow and concentration field discretization. Salt concentration accumulation along HFM surfaces was examined, and it was reported that the transmembrane concentration gradient depends on the feed-side surface concentration as well as the permeate side surface concentration, which varies along the length of the membrane. The production-side

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Nomenclature

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_f	Skin friction coefficient
c_p	Production side membrane concentration [kg/m^3]
c_w	Feed side membrane concentration [kg/m^3]
COP_s	Coefficient of performance of module
d	Hydraulic diameter [m]
D	Diffusion coefficient [m^2/s]
f	Friction factor
h_m	Mass transfer coefficient [m/s]
$\vec{n}$	Surface normal unit vector
Δp	Transmembrane pressure difference [Pa]
P_w	Wetted perimeter [m]
r	Radial distance [m]
Re	Reynolds number
Sc	Schmidt number
Sh	Sherwood number
T	Temperature [$^{\circ}$C]
$\vec{V}\ (u, v, w)$	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

ϕ	Product recovery rate [−]
κ	Osmotic coefficient [kPa m^3/kg]
μ	Dynamic viscosity [Pa s]
ν	Kinematic viscosity [m^2/s]
ω	Vorticity magnitude [1/s]
$\Delta\pi$	Osmatic pressure [Pa]
ρ	Density [kg/m^3]
$\tau_{\max}$	Maximum wall shear stress
τ_w	Normalized wall shear stress

Subscripts

i and j	Index notation
w	Properties along the surface of membrane

salt concentration was nearly uniform but nonetheless decreased slightly along the module length.

Accurately capturing local changes in concentration near to and along HFM surfaces is also very important because fouling has been shown to increase the system pressure drop, thereby demanding increased pumping power. Ghidossi et al. [9] conducted numerical simulations to elucidate the relationship between pressure drop and operating/design parameters such as inlet velocity, inlet pressure, internal diameter, and permeability for a HFM ultrafiltration system. Their model relates the pressure drop across the module length, or energy loss, to membrane fouling. The model they employed is experimentally validated and suggests that higher flow speeds increase system performance. Villafafila and Mujtaba [10] also discussed the relation of fouling to pressure drop. They carried out simulations using algebraic equations to optimize design and operating parameters for HFM water desalination modules. In that study, simulations were conducted by specifying the output of one HFM module as the input of a subsequent module. This approach helped them understand the physical behavior of and optimal parameter selection for the RO-driven water desalination process using HFMs. However, their algebraic model must be improved in order to accurately incorporate the effects of concentration polarization.

Our approach to increasing momentum mixing throughout the module involves the introduction of a twist to the traditional HFM module design. Others have studied similar design alterations and varying operating parameters. Pak et al. [11] employed finite difference methods to solve for the flow and concentration fields in a two-dimensional HFM to investigate the effects of different operating conditions on CP. They reported that concentration boundary layer thickness decreases with increasing Reynolds numbers. Anqi et al. [12] investigated the effect of various flow speeds and HFM arrangements in modules of the radial flow configuration. They carried out steady-state and transient CFD simulations in two-dimensional domains by means of the k-ω Shear Stress Transport (SST) turbulence model. They found that transient effects profoundly influence CP. Motevalian et al. [13] used CFD simulations to determine the flow characteristics inside a twisted, elliptical, and helically-coiled cylindrical single hollow tube for Reynolds number of up to 200. In that study, the flow field was characterized, but not the concentration field, and special attention was given to the wall shear stress and vorticity. Also, they considered no-slip and no-penetration boundary condition by neglecting the permeate suction along the membrane surfaces. They found that twisted, elliptical tubes provide more wall shearing than its helically-coiled and straight counterparts, but with the penalty of a 50% greater pressure drop. Motevalian et al. showed that these geometric tube adaptations induce flow instabilities and vortical activity which are expected to enhance mass transfer by re-suspending particles accumulated along membrane surfaces back into the bulk flow and facilitate more clean water passage through membrane surfaces. Teoh et al. [14] experimentally investigated the effect of twisted, braided, and baffled HFMs on the heat-transfer coefficient for direct contact membrane distillation modules. They reported 36% flux enhancements for braided and twisted HFMs without any additional mixing promoters.

To the best of our knowledge, flow and concentration field characterization with proper membrane boundary conditions throughout a twisted RO HFM module has not yet been reported on. This study characterizes and compares the flow structures and performance of twisted and straight, co-axially aligned three-dimensional HFM modules. To compare system performance, we consider the permeate fluxes of both geometries relative to their required pumping power. It will be shown that the twisted HFM geometry outperforms the straight, co-axially aligned geometry despite additional necessary pumping power due to increased system friction. System performance will be evaluated by Sherwood number, friction factor, the coefficient of performance, and transmembrane permeate mass flux.

2. Model descriptions

2.1. Governing equations

Incompressible, steady-state laminar Newtonian fluid motion is governed by the Navier-Stokes and conservation of mass equations, and the salt concentration field is described by the mass transport equation. With constant physical properties, these equations are expressed as:

$$(\vec{V}\cdot\nabla)\vec{V} = \frac{1}{\rho}\nabla p + \nu\nabla^2\vec{V} \tag{1}$$

$$\nabla\cdot\vec{V} = 0 \tag{2}$$

$$(\vec{V}\cdot\nabla)c = D\nabla^2 c \tag{3}$$

The binary brine mixture has density, ρ, pressure, p, and kinematic viscosity, ν. The scalar salt concentration is given by c, and the diffusion