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Investigation into the effectiveness of feed spacer configurations for reverse osmosis membrane modules using Computational Fluid Dynamics

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ABSTRACT

Reverse osmosis operations for water treatment are usually energy intensive and responsible for most of the product price. Several studies used flow characteristics to compare different geometries of feed spacers, but these cannot completely explain the effectiveness of feed spacers for promoting mass transfer near membranes. A few recent studies introduced a concept (Spacer Configuration Efficacy, SCE) combining mass transfer and energy consumption, but SCE has been applied only to a limited extent.

The present study uses 3-dimensional steady state Computational Fluid Dynamics with mass transfer to compare four channels with feed spacer configurations (Ladder-type, Triple, Wavy and Submerged) and an empty plain channel using SCE and other performance measures. In contrast to previous studies, a saturated concentration boundary condition is employed at the membrane surface and optimised meshing of the domain is discussed. Power law correlations for SCE and other performance measures developed from the simulation results enable quick evaluation of the spacers.

Results indicated that the assumed saturated solute concentration at the membrane strongly affects the mass transfer coefficient. Based on SCE, the Wavy spacer configuration showed the highest performance for $Re > 120$ among the obstructed geometries considered, while Ladder-type was better for $Re < 120$.

1. Introduction

Reverse osmosis (RO) is a common approach to water desalination, mostly used for brackish water in medium to large scale facilities as well as small scale home applications. It relies on an imposed pressure difference to drive the transfer of the desired permeate, water, through a semi-permeable membrane. The membrane is supposed to stop dissolved species and emulsified particles from passing through to the permeate side. Two of the main challenges in RO desalination are reducing energy consumption and the build-up of deposits on the membrane surface leading to frequent outages. Several studies have focussed on different RO membrane variations, helping the desalination industry to have a better understanding of RO modules and to minimize desalination costs.

RO plants require the minimum amount of energy per unit product among the different desalination technologies available today industrially: multi-stage flash, multi-effect distillation, mechanical vapour compression and reverse osmosis [2]. One of the most readily available designs of RO systems is the Spiral Wound Module (SWM), which is made of repeated sandwiches of flat membrane sheets separated by a thin mesh spacer material (Fig. 1). This combination is rolled around a central tube and fitted into a cylindrical body. As the feed flows through the module, a portion passes through the membrane surface, leaving behind a rich brine and producing permeate, which flows into the central collecting tube [3]. SWMs are a compact and cheap option for RO designs offering a high mass transfer area to volume ratio, which leads to high volumetric throughput and moderate energy consumption. In the last few years, several studies have investigated mass transport phenomena or fluid flow to optimize the performance of SWMs. Most of them focused on temperature polarization [4], fluid flow patterns and characteristics [5–9], membrane performance [10] or particle deposition [11]. Limited studies tried to optimize the performance of the modules by changing the spacer configuration to reduce energy consumption and particle deposition while also maximizing fluid mixing and recirculation zone effects. Good spacer configurations should minimize build-up of deposits and concentration polarization by keeping the concentration of the solute in the fluid layer in contact with membrane close to the bulk concentration [5,6,12–14]. Table 1 presents a summary of studies conducted on selected SWM spacer configurations from the early 1980s to present.

In general, more mixing in the fluid and more effective recirculating zones will keep mass transfer resistance low and the membrane

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Nomenclature

A_{eff}	effective area (m^2)
A_i	area of inlet face (m^2)
C_i	inlet salt concentration (w/w)
C_m	membrane salt concentration (w/w)
$\mathcal{D}$	mass diffusivity (m^2/s)
d	filament diameter (m)
D_h	hydraulic diameter (m)
Eu	Euler number
H	channel height (m)
k	average mass transfer coefficient (m/s)
L	channel length (m)
n	distance in direction normal to the filament (m)
P_0	ambient pressure (Pa)
ΔP	pressure drop (Pa)
ΔP^*	dimensionless pressure drop
Pn	power number
Re_{ch}	channel Reynolds number
Re_{cyl}	cylinder Reynolds number
Re_h	hydraulic Reynolds number
SCE	Spacer Configuration Efficacy
Sh	Sherwood number
SPC	Specific Power Consumption (W/m^3)
u_{eff}	effective velocity (m/s)
u	velocity in x direction (m/s)
$\dot{V}$	volumetric flowrate (m^3/s)
v	velocity in y direction (m/s)
W	channel width (m)
w	velocity in z direction (m/s)

Greek symbols

α	flow angle of attack (°)
β	spacer geometry angle (°)
ϵ	porosity
μ	dynamic viscosity (Pa s)
ρ	density (kg/m^3)

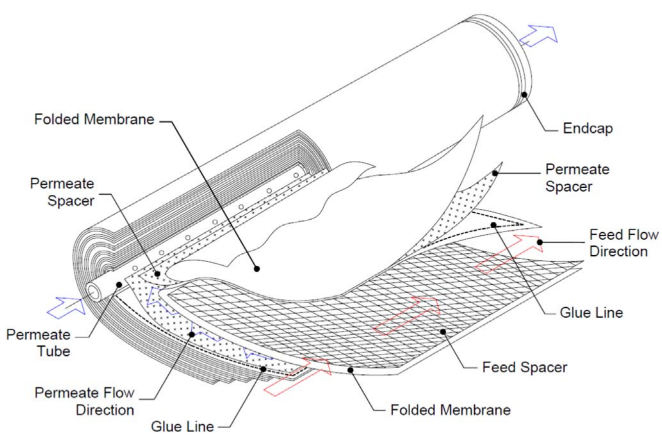

Fig. 1. Configuration of a typical spiral wound module used for reverse osmosis desalination [1]. Reprinted with permission of publisher.

unblocked. Both effects are characterised by the Sherwood number, Sh. On the other hand, more mixing and flow recirculation means more energy consumption. The final decision on membrane configuration and operating conditions is a trade-off between higher mass transfer rates and longer service intervals between cleaning on one hand, and greater energy costs on the other.

A recent study [13] proposed a dimensionless number that captures both mass transfer, in the form of the Sherwood number, and the energy required for flow, in the form of the Power number, Pn. This dimensionless number, the Spacer Configuration Efficacy (SCE) is defined as Sh/Pn. SCE quantifies mixing quality on the feed side of the membrane for different feed spacer arrangements. Due to its definition, a higher SCE represents a smaller solute concentration difference between the bulk fluid and that near the membrane surface, or a lower pumping energy requirement per unit of permeate. Both mixing quality and recirculating flows will directly influence a unit's energy consumption and increase the maintenance intervals. Saeed et al. [13] defined the SCE concept and also studied the effect of Re on Pn, Sh, SPC and SCE for Ladder-type spacers and suggested the best geometrical arrangement to use among the different Ladder-type cases studied, but this study needs to be extended to investigate the SCE concept for other spacer configurations.

The main goal of this study is to extend the application of SCE to other spacer geometries and to compare spacer behaviour for varying Reynolds numbers in the laminar regime, up to Re=200, in terms of both flow characteristics and mass transfer phenomena. Computational Fluid Dynamics (CFD) will be used to simulate the flow and mass transfer phenomena. Along with commonly reported measures like pressure drop, power consumption and Sherwood number, SCE will also be evaluated from the CFD results, which will allow SCE to be compared against those conventional measures of spacer performance.

2. Simulation approach

2.1. Geometries studied

In the current work, five spacer geometries have been studied as shown in Fig. 2. Selecting these geometries is based on their wide-spread use and the availability of data from previous studies, which makes it possible to compare the results. For each geometry, only a representative portion of the fluid flow domain is shown in Fig. 2. The Ladder-type geometry (Fig. 2a) consists of a layer of straight latitudinal filaments positioned on top of a layer of straight longitudinal filaments to form a square pattern. The Triple geometry (Fig. 2b) is a Ladder-type arrangement with a third layer of straight latitudinal filaments added below in the z direction. In the Wavy geometry (Fig. 2c), straight latitudinal filaments are located alternatively adjacent to the top and bottom membranes with sinusoidal longitudinal filaments weaving between them. The Submerged geometry (Fig. 2d) has latitudinal filaments only, positioned midway between the top and bottom membranes. Finally, the Plain geometry (Fig. 2e) represents an unobstructed channel between two parallel membrane surfaces; that is, no spacer filaments are present in this geometry. All filaments are assumed to have a circular cross-section which, while not exactly true for commercial spacers, is a reasonable assumption [37].

Biplanar feed spacer geometries are most the most widely used type for RO modules [1], which means both Plain and Triple are not common choices for membrane systems, but they are included for comparison purposes with the other more conventional configurations.

2.2. Parameters considered for simulation

2.2.1. Hydraulic diameter (D_h)

The hydraulic diameter, D_h, is defined as

$$D_h = \frac{4 \times \textit{volume occupied by fluid}}{\textit{surface area of wetted walls}} \tag{1}$$

For flow in membrane channels with spacer filaments, this becomes [16]