Desalination 426 (2018) 108–117

Contents lists available at ScienceDirect

Desalination

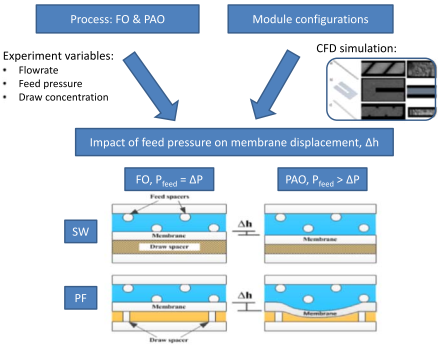
journal homepage: www.elsevier.com/locate/desal

Impact of module design in forward osmosis and pressure assisted osmosis: An experimental and numerical study

Boyue Lian[a], Gaetan Blandin[b], Greg Leslie[a], Pierre Le-Clech[a,*]

[a] UNESCO Centre for Membrane Science and Technology, School of Chemical Engineering, The University of New South Wales, NSW2052 Sydney, Australia
[b] LEQUIA, Institute of the environment, University of Girona, Campus Montilivi, Girona, Spain

GRAPHICAL ABSTRACT



ARTICLE INFO

Keywords:
Pressure drop
Membrane module design
Computational fluid dynamics
Flow channel narrowing

ABSTRACT

An experimental and computational fluid dynamic (CFD) study is reported for two forward osmosis (FO) module configurations, i.e. spiral wound (SW) and plate and frame (PF), featuring two types of draw channel spacers. Modules were operated both in FO and pressure assisted osmosis (PAO) modes. By varying the cross flow velocities (CFV), inlet feed pressures ($P_{\text{Feed-in}}$) and draw solution concentrations, FO module performance, reported in terms of pressure drop and water flux, was evaluated. The experiment results showed that the increase of $P_{\text{Feed-in}}$ raised the draw channel pressure drop by 37% for SW module and around 4 folds for PF module. Additional feed side pressure also unexpectedly decreased the water flux by 28% for PF module with 35 g L^{-1} red sea salt draw solution. Such results indicated significant changes of both feed and draw flow channels height. This phenomenon was defined as relative displacement of membrane, which was quantified by validated CFD simulation. The results suggested that $P_{\text{Feed-in}}$ can induce the displacement of membrane in the PAO mode. Based on CFD simulation, 100 and 200 μm membrane displacements were predicted for SW and PF modules, respectively operated at 4 bar feed pressure, resulting in significant impact in process performance.

1. Introduction

The recent development and commercialization of forward osmosis (FO) modules has accelerated research activities in this field by five folds for the last 5 years [1–4]. In particular, recent studies have demonstrated the potential of FO for the concentration of food and beverages, delivery of pharmaceutical [5–7], and the development of synergistic desalination and water reuse systems [8,9]. Several reviews

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[*] Corresponding author at: UNESCO Centre for Membrane Science & Technology, School of Chemical Engineering, Building F10, The University of New South Wales, Sydney NSW 2052, Australia.
E-mail address: p.le-clech@unsw.edu.au (P. Le-Clech).

http://dx.doi.org/10.1016/j.desal.2017.10.047
Received 30 August 2017; Received in revised form 23 October 2017; Accepted 23 October 2017

Nomenclature and unit

A	Water permeability, $L\ m^{-2}\ h^{-1}\ bar^{-1}$
A_c	The area perpendicular to the direction of flux in the mesh cell at membrane liquid interface, m^2
C_{kc}	Kozeny-Carman constant
C_{Draw}	Draw side concentration, $g\ L^{-1}$
C_{Feed}	Feed side concentration, $g\ L^{-1}$
h	Selected flow channel height, mm
Δh	Relative membrane displacement, μm
J_w	Water permeation flux, $L\ m^{-2}\ h^{-1}$
J_s	Salt permeation flux, $g\ m^{-2}\ h^{-1}$
ΔP	Pressure drop, bar
P_{Draw}	Draw side pressure on membrane surface, Pa
$P_{Draw\text{-}in}$	Draw side inlet pressure, bar
$P_{Draw\text{-}out}$	Draw side outlet pressure, bar
P_{Feed}	Feed side pressure on membrane surface, Pa
$P_{Feed\text{-}in}$	Feed side inlet pressure, bar
$P_{Feed\text{-}out}$	Feed side outlet pressure, bar
R	Rejection rate, %
R_g	Gas constant as 0.08206 $L\ atm\ mol^{-1}\ K^{-1}$
S_m	Mass source term for transmembrane mass flux, $kg\ m^{-3}$
S_v	Momentum source term for transmembrane mass flux, $kg\ m^{-3}$
S_i	Momentum source term for resistance created by porous media, $kg\ m^{-3}$
Δt	Total thickness of FO unit with a membrane and two flow channels, mm
TMP	Transmembrane pressure, bar
V	Volume for a single mesh cell at membrane liquid interface, m^3
v	Velocity, $m\ s^{-1}$

Greek symbols

α	Porous media permeability, $kg\ m^{-2}\ s^{-1}\ Pa^{-1}$
μ	Kinetic viscosity, $m^2\ s^{-1}$
ε	Porosity
ρ	Density, $kg\ m^{-3}$
π_{Draw}	Osmotic pressure on membrane surface at draw side, Pa
π_{Feed}	Osmotic pressure on membrane surface at feed side, Pa

have also identified a suite of technical barriers to be addressed including, mass transfer limitations of existing modules [5,10,11], presence of internal concentration polarization [10,12], and the need to minimize fouling [13], maximise rejection of trace organic contaminants [14], develop more efficient draw solutions [12,15,16] and optimise energy requirements [17,18]. Recently, the development of pressure assisted osmosis (PAO) operation has partially addressed the issues of water flux and selectivity through judicious management of osmotic and hydraulic pressure driving forces [19–21]. However, further research focussing on scale-up operation and module design are expected. Regrettably, the literature on FO module development and pilot studies is very limited, and represents less than 5% of peer-reviewed studies in the last five years.

Currently, a majority of FO module designs have been directly adopted from spiral wound (SW) reverse osmosis (RO) module [22–25]. Due to the difference between functionalities of FO draw and RO permeate channels, special attention has to be taken when designing the characteristic of FO draw channels and its spacers to achieve optimum hydraulic conditions. Low porosity spacer, such as dense woven plastic fabric has usually been applied to RO permeates, due to 1) the absence of concentration polarization on the permeate side; 2) the relative low pressure variance, due to the low flowrate, and 3) the need to support membrane from deformation due to the significant transmembrane pressure (TMP) [26,27]. However, FO processes rely on circulation of draw side fluid to minimize concentration polarization and maintain high osmotic pressure. The high flowrate in the draw side associated with low porous spacer can create significant pressure drop, which disrupt the transmembrane mass transfer [23,25]. Previous studies have also demonstrated that FO membranes can be deformed even when moderate pressure is applied, potentially narrowing the draw channel. As such, tricot spacers are usually preferred in SW modules to limit membrane deformation [20,23,28,29]. However, even if the membrane deformation is avoided, variation in the height of the flow channels could occur through the relative displacement of the membrane, and still need to be studied. Such phenomenon is expected to affect water flux and increase energy requirements; however, only limited information has been reported on the combining effect of cross flow velocity (CFV) and feed spacer design on membrane displacement.

Literature also shows that the combination of experimental and numerical techniques, such as computational fluid dynamic (CFD), can be used as a powerful tool to optimise membrane, module and system design [30–33]. To date, systematic evaluation of the hydrodynamics of FO modules has involved the adaptation of standard mass transfer models and the use of two dimensional steady state simulations [34]. The effect of different spacers on the turbulence promotion efficiency and the concentration polarization for FO membrane was then studied using film theory to predict mass transfer [35]. Similarly, the effect of module design, especially hypothetical spacer configuration and CFV, on membrane mass transfer was studied for both FO and pressure retarded osmosis process [36,37]. However, most of literature on FO module simulation focused on the prediction of water flux, while other parameters affecting FO module operating efficiency, such as pressure drop and deformation of flow channel, have not been fully explored. Previous studies have also focused on a small region of the FO module (particularly near membrane area), while the hydraulic behaviour in the entire FO module has not been fully explored. Of particular interest, CFD is capable of dealing with complex fluid flow in confined geometry created by spacer and can provide precise estimation on pressure change, making it an appropriate tool to study the hydraulic changes induced by operating conditions and spacers.

Thus, this study aims to assess module pressure drop as a function of CFV, channel dimension and spacer type for different FO module configurations, to identify appropriate operation conditions and spacer designs for large scale FO/PAO systems. The approach uses experimental data for SW as well as plate and frame (PF) FO modules to build three dimensional CFD models to study the impact of operating CFV, pressure, draw side spacers and mass flux on the hydraulic behaviour of fluid flow in both feed and draw channels. The CFD model will be validated with experimental pressure drop data and will in turn be used to demonstrate the impact of relative membrane displacement on module hydraulic performances with different FO draw side spacers.

2. Materials and methods

2.1. FO membrane modules

Commercially available SW and PF modules were supplied by Hydration Technologies Innovation (HTI, Oregon USA) and Porifera Incorporated (California, USA) (Table 1). It is to be noted that HTI ceased activity in 2016. The HTI SW modules (Model No. 2521FO-MS) used cellulose triacetate (CTA) membranes cast on a non-woven backing and featured a 1.14 mm thick diamond-type polypropylene feed channel spacer and three layers of permeate carrier for the draw channel. The difference between the SW FO and standard RO modules