Desalination 434 (2018) 100–120

Contents lists available at ScienceDirect

Desalination

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

Osmotic's potential: An overview of draw solutes for forward osmosis

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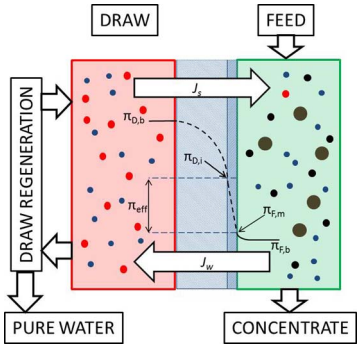
GRAPHICAL ABSTRACT



ARTICLE INFO

Keywords:
Forward osmosis
Draw solution
Membrane separation
Desalination
Water treatment

ABSTRACT

Forward osmosis (FO) is a membrane separation process using a highly concentrated draw solution with high osmotic potential to draw water across a semi-permeable membrane from a feed source. This feed source may be seawater, wastewater or other natural or contaminated water sources. Unlike other membrane driven purification processes, the product is not clean water, but a diluted draw solution. As a result a second step is often needed to produce a pure water product. A major advantage of FO is that the low hydrodynamic pressure involved leads to lowered fouling of membranes and greater flux recovery after cleaning, as well as often providing a low energy process which can recover clean water from difficult or highly fouling sources. Selection of an appropriate and effective draw solution is essential for the practical operation of an FO process. This review will give an overview of the theoretical underpinnings of draw solution performance and a comprehensive summary of the current literature regarding the different types of draw solutions which have been investigated and their respective benefits and detriments.

1. Introduction

Amongst the several membrane based technologies currently being developed, the process of forward osmosis (FO), also known as manipulated osmosis, is showing great promise, particularly for treatment of hypersaline, high fouling or otherwise challenging feed waters [1–8]. Unlike pressure driven membrane processes, such as reverse osmosis (RO), instead of pumping the feed water at a pressure sufficient to overcome the osmotic pressure difference between the feed and permeate, with FO it is the difference in osmotic pressure between the feed water and a more concentrated draw solution which drives the filtration process. As a result, the initial filtration step requires less

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http://dx.doi.org/10.1016/j.desal.2017.09.017
Received 8 August 2017; Received in revised form 14 September 2017; Accepted 16 September 2017
Available online 27 September 2017

Abbreviations

BSA	bovine serum albumin
CA	citric acid
CQD	carbonised quantum dot
DI	de-ionised
DME	dimethyl ether
ECP	external concentration polarization
EDTA	ethylene diamine tetra-acetic acid
$Fe(acac)_3$	ferric triacetylacetonate
FO	forward osmosis
HA	hyaluronic acid
ICP	internal concentration polarization
LCST	lower critical solution temperature
MD	membrane distillation
MED	multi-effect distillation
MFC	magnetic field control
MSF	multi-stage flash
NF	nanofiltration
P_{4444} DMBS	tetra butyl phosphonium 2,4 dimethyl benexene sulfonate
P_{4444} TMBS	tetra butyl phosphonium mesitylene sulfonate
P_{4448} Br	tri butyl octyl phosphonium bromide
PAA	poly acrylic acid
PAM	poly(acrylamide)
PDMAEMA	poly(2-(dimethylamino) ethyl methactylate)
PEG	poly(ethylene glycol)
PNIPAM	poly(*N*-isopropylacrylamide)
PRO	pressure retarded osmosis
PSA	poly (sodium acrylate)
PSA-NIPAM	poly(sodium acrylate)-*co*-poly(*N*-isopropyl acrylamide)
PSS	poly (sodium-4-syrenesulfonate)
PSSS-PNIPAM	poly(sodium styrene-4-sulfonate-*co*-*N*-isopropylacrylamide)
PVA	poly (vinyl alcohol)
RO	reverse osmosis
SPS	switchable polarity solvents
TEM	transmission electron microscopy
TMA	tri-methylamine
TREG	tri-ethylene glycol
UF	ultrafiltration

Symbol

A	water permeability coefficient
B	solute permeability coefficient within membrane
B_2, B_3, B_4…	virial coefficients
B^A	solute permeability coefficient for the active layer
c	mass concentration of solutes
C_D	draw solute concentration
C_F	feed solute concentration
D	solute diffusion coefficient
D^A	draw solute diffusion coefficient through active layer
D_{eff}	effective solute diffusion coefficient
d_h	hydraulic side of flow channel
d_p	pore diameter
d_s	solute molecular diameter
H	partition coefficient
J_s	solute flux
$J_{specific}$	specific reverse solute flux
J_w	water flux
K	solute resistivity to flow through porous membrane
k_d	mass transfer coefficient for draw solution side
k_f	mass transfer coefficient for feed solution side
k_m	mass transfer coefficient for membrane support layer
M	molar concentration
n	number of ions produced by draw solute dissolution
N_p	number of ions
R	fractional salt rejection
R_g	ideal gas constant
S	membrane structural parameter
Sh	Sherwood number
T	absolute temperature (K)
t_A	membrane active layer thickness
t_s	membrane support layer thickness
V	solution volume
δ	membrane constrictivity parameter
ΔC	concentration gradient of solute across active layer
ε_{eff}	effective porosity
π	osmotic pressure
$\pi_{D,b}$	bulk osmotic pressure of draw solution
$\pi_{D,i}$	osmotic pressure within support layer adjacent to active layer
$\pi_{D,m}$	osmotic pressure close to membrane (draw side)
$\pi_{F,b}$	bulk osmotic pressure of feed solution
$\pi_{F,m}$	osmotic pressure at membrane active layer (feed side)
σ	reflection coefficient
τ	membrane tortuosity
ϕ	osmotic pressure coefficient

applied energy and suffers from lower fouling and scaling, with greater fouling reversibility observed subsequent to cleaning measures [9]. However, unlike other membrane processes, the end product of FO is not purified water, but rather a diluted draw solution. As a result, unless the diluted draw solution is of use of itself or the process is purely being run to dewater the feed rather than produce a useful product water, then a second separation step is necessary to both re-concentrate the draw solution for reuse and to produce a purified water product. The regeneration step requires additional energy, which in some cases may push the total energy costs above that of alternatives, such as RO or membrane distillation (MD). Shaffer et al. [3] analysed the energy efficiency of the FO process in light of this necessary regeneration step from a thermodynamic perspective, particularly in comparison with RO processes. They pointed out that the energy needed to run an FO process with draw solute regeneration cannot be less than the minimum energy of separation, a minimum which is already close to the operating parameters of recent RO designs [10]. Furthermore, they point out that if using a regeneration process such as ultrafiltration (UF), which typically has higher water flux and would be suitable for regeneration of larger sized solutes, the energy required to re-concentrate the draw solution to its original osmotic potential would require the same energy as for using RO, as the amount of energy needed is based on the osmotic pressure difference between the concentrated and diluted draw solutions, not on the process itself [3]. In addition Field and Wu [11] studied mass transfer limitations when scaling up FO processes and found them to be more severe for FO than for other membrane applications as module size is increased, making FO less favourable at large scale than RO for seawater desalination.

However, FO still has much potential for treating hypersaline streams too concentrated for RO [12], dewatering wastewater [4,8,13,14], concentrating foods [15,16] or niche applications where draw solute does not need regeneration, such as using fertilizer as the draw solute which can then be utilized for fertigation applications [14,17–19]. In addition much research has been applied to the energy