Concentration polarization on surface patterned membranes

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Abstract

Surface pattern is a promising approach to enhance membrane performance while contradictory results have been reported on concentration polarization of patterned membranes. Here, we provide an experimental and modeling study of the concentration polarization on patterned membranes by varying pattern size, solute size, surface hydrophilicity and membrane orientation. Interesting trends were observed when comparing different membrane orientation, where relative concentration polarization degree (CPD) was found to be dependent on molecular weight. Salts and small organic molecules encountered more severe CPD in the transverse mode, while molecules larger than a threshold value showed a different trend. Such threshold molecular weight increased at larger pattern size. Simulation results were consistent with experimental observations, and revealed the critical role of diffusivity on such phenomena. Results also showed more severe concentration polarization on patterned membranes in both parallel and transverse modes in most cases, compared to smooth membrane.

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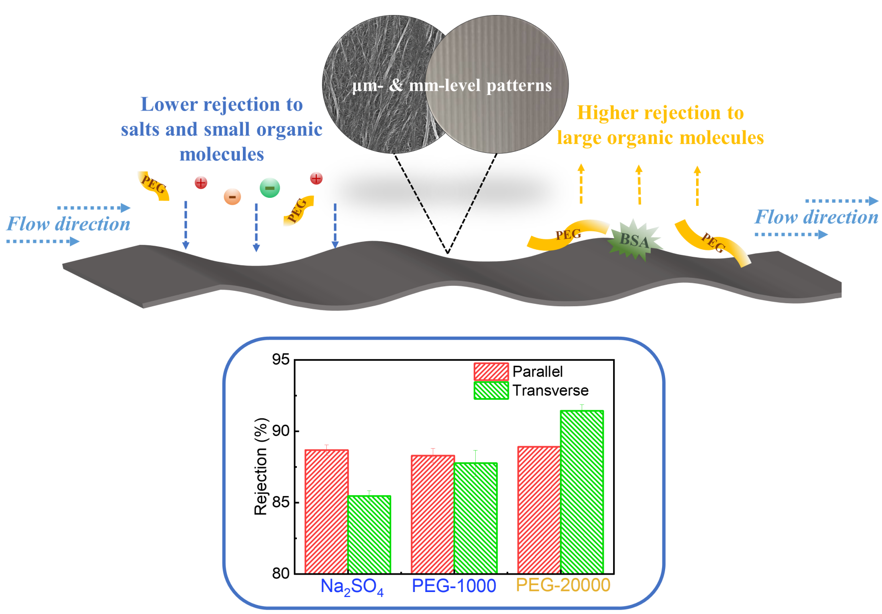
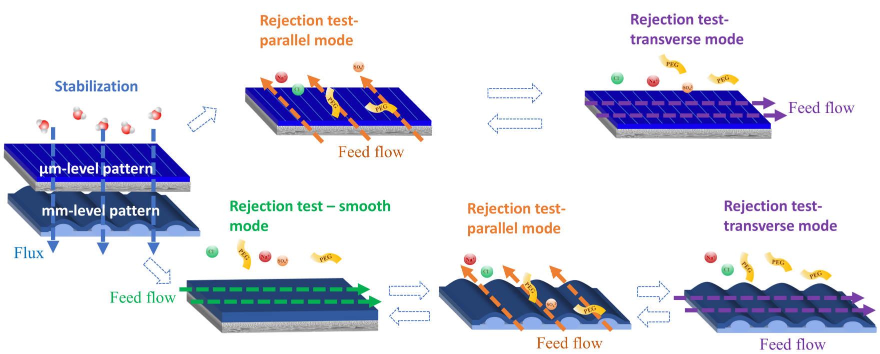
`Manuscript_Concentration_polarization.docx` available at https://authorea.com/users/466115/articles/560499-concentration-polarization-on-surface-patterned-membranes

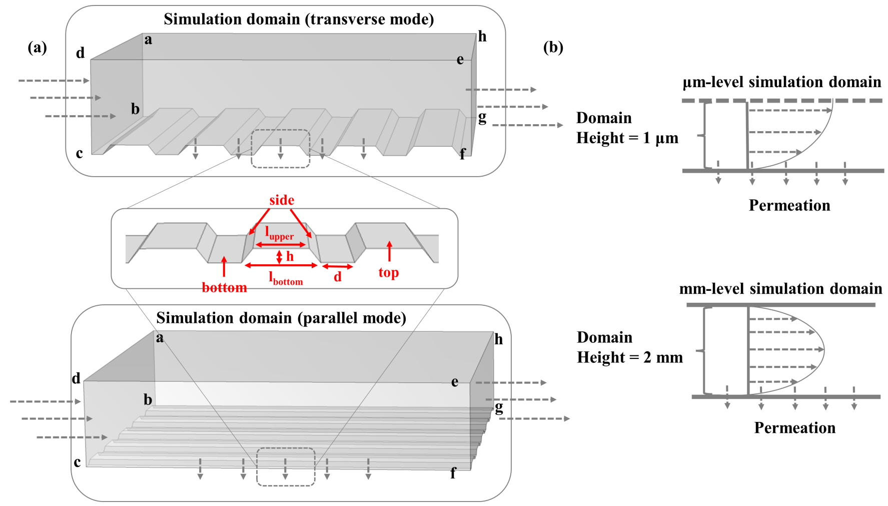


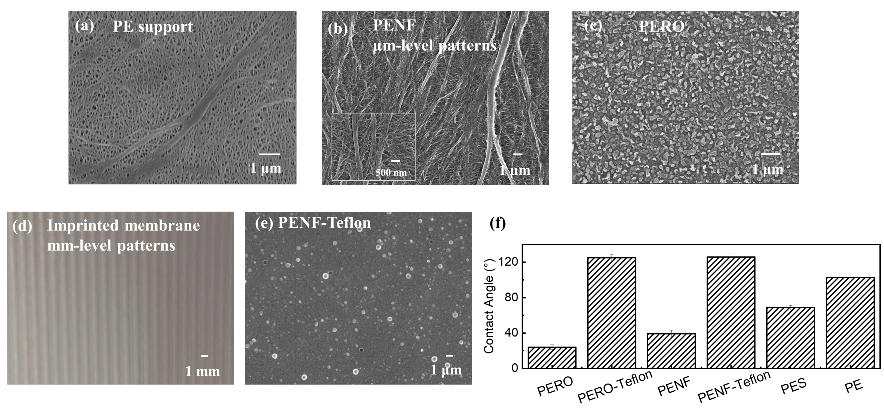
Membrane	Pattern	Solute in the feed	Feed concentration, ppm
PENF	µm	Na_2SO_4	2000
PENF	µm	PEG-400	200
PENF	µm	PEG-400	3000
PENF-2h	µm	PEG-1000	200
PENF-4h	µm	PEG-4000	200
PENF-8h	µm	PEG-20000	200
PERO	mm	NaCl	2000
PENF	mm	PEG-400	200
PERO-48h	mm	PEG-20000	200
PES	mm	BSA	200
PE	mm	PEG-1M	200
PENF-Teflon	mm	Na_2SO_4	2000
PERO-Teflon	mm	NaCl	2000
PENF-2h-Teflon	mm	PEG-600	200

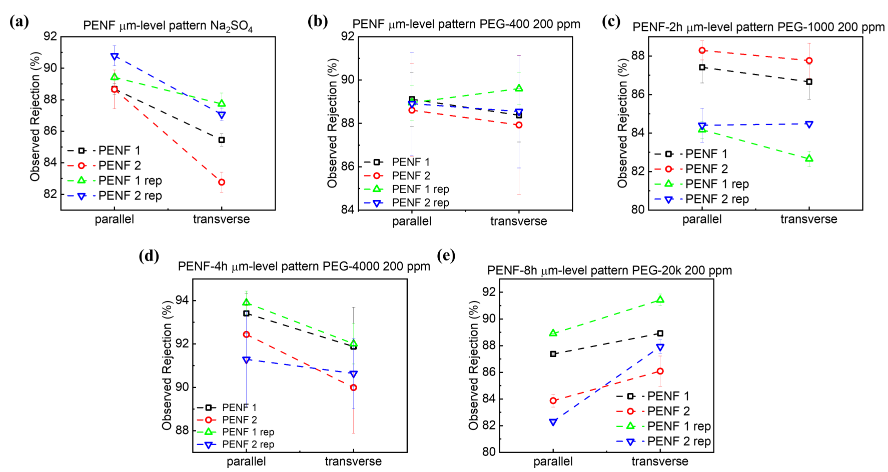
Boundary designation	Fluid Flow	Solute Transport
Inlet (a-b-c-d/c-d-e-f)	Fully developed flow, u_{inlet}	$c_{in} = c_{solute}$
Outlet (e-f-g-h/a-b-g-h)	P = 5 bar	Outlet
Side wall (a-b-g-h/e-f-g-h)	$u_{a\text{-}b\text{-}g\text{-}h} = u_{c\text{-}d\text{-}e\text{-}f}$	$c_{a\text{-}b\text{-}g\text{-}h} = c_{c\text{-}d\text{-}e\text{-}f}$
Side wall (c-d-e-f/a-b-c-d)	$u_{c\text{-}d\text{-}e\text{-}f} = u_{a\text{-}b\text{-}g\text{-}h}$	$c_{c\text{-}d\text{-}e\text{-}f} = c_{a\text{-}b\text{-}g\text{-}h}$
Upper wall (a-d-e-h)	Moving wall, $u_{H=adeh} = u(H = 1\mu m)$	Impermeable
Permeable membrane(b-c-f-g)	$u = Permeability \times Pressure$	$c_{outlet} = 0.1c$

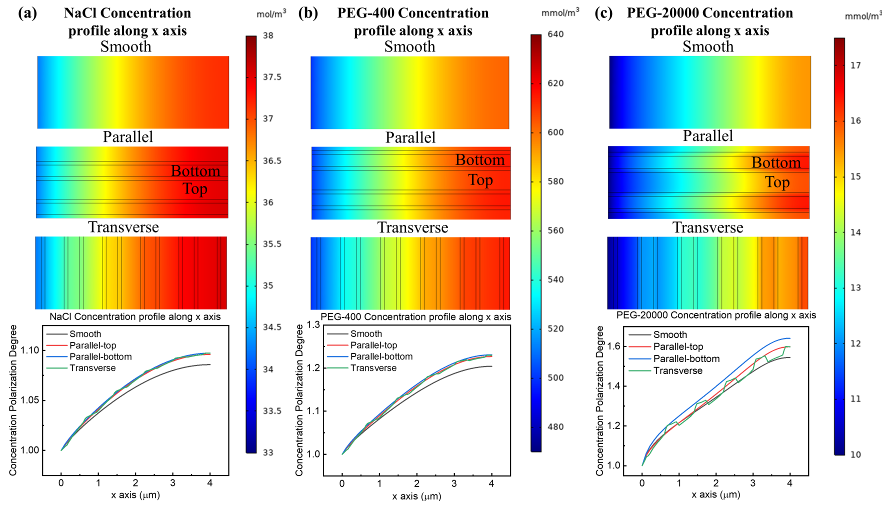
Boundary designation	Fluid Flow	Solute Transport
Inlet (a-b-c-d/c-d-e-f)	Fully developed flow, $u_{inlet} = 13.9\ cm/s$	$c_{in} = c_{solute}$
Outlet (e-f-g-h/a-b-g-h)	P = 5 bar	Outlet
Side wall (a-b-g-h/e-f-g-h)	$u_{a\text{-}b\text{-}g\text{-}h} = u_{c\text{-}d\text{-}e\text{-}f}$	$c_{a\text{-}b\text{-}g\text{-}h} = c_{c\text{-}d\text{-}e\text{-}f}$
Side wall (c-d-e-f/a-b-c-d)	$u_{c\text{-}d\text{-}e\text{-}f} = u_{a\text{-}b\text{-}g\text{-}h}$	$c_{c\text{-}d\text{-}e\text{-}f} = c_{a\text{-}b\text{-}g\text{-}h}$
Upper wall (a-d-e-h)	$u_{H=adeh} = 0$	Impermeable
Permeable membrane(b-c-f-g)	$u = Permeability \times Pressure$	$c_{outlet} = 0.1c$

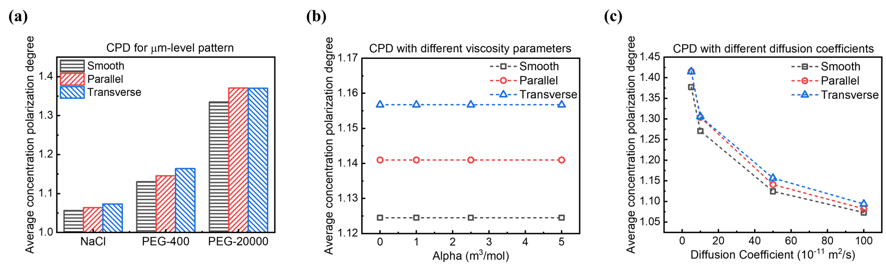


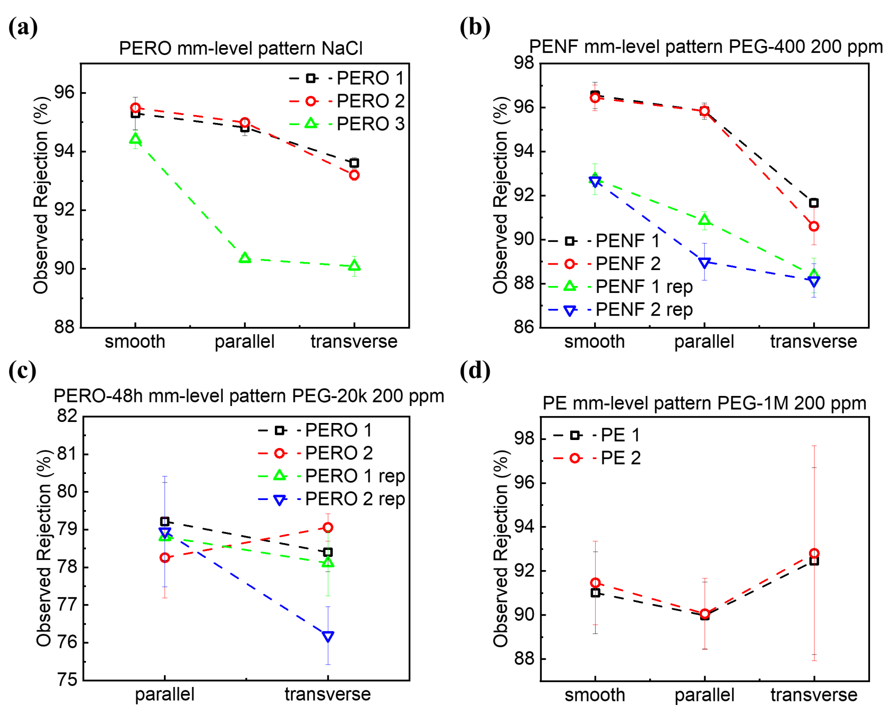

(a)
Simulation domain (transverse mode)
a
b
c
d
e
f
g
h
side
l_{upper}
h
l_{bottom}
d
bottom
top
Simulation domain (parallel mode)
(b)
μm-level simulation domain
Domain
Height = 1 μm
Permeation
mm-level simulation domain
Domain
Height = 2 mm
Permeation

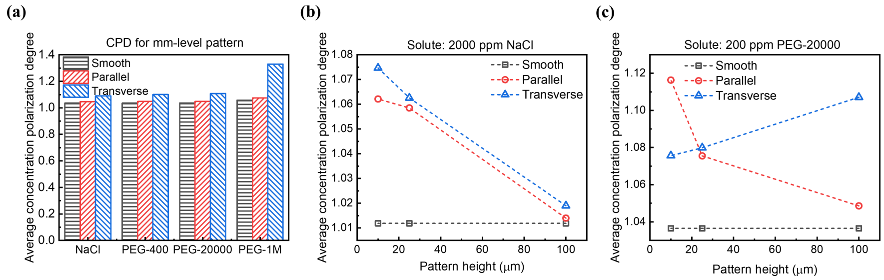

(a) PE support
1 μm
(b) PENF
μm-level patterns
500 nm
1 μm
(c) PERO
1 μm
(d) Imprinted membrane
mm-level patterns
1 mm
(e) PENF-Teflon
1 μm
(f)
Contact Angle (°)
PERO
PERO-Teflon
PENF
PENF-Teflon
PES
PE

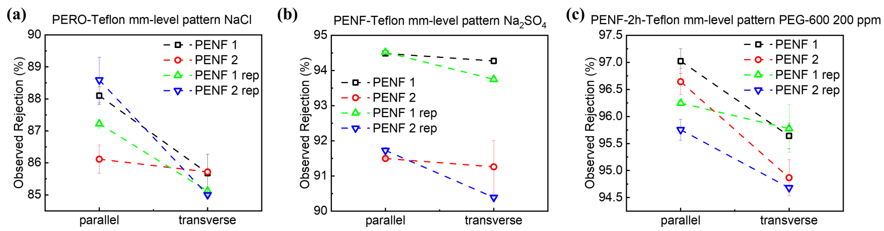

(a)
PENF μm-level pattern Na_2SO_4
Observed Rejection (%)
PENF 1
PENF 2
PENF 1 rep
PENF 2 rep
parallel
transverse
(b)
PENF μm-level pattern PEG-400 200 ppm
(c)
PENF-2h μm-level pattern PEG-1000 200 ppm
(d)
PENF-4h μm-level pattern PEG-4000 200 ppm
(e)
PENF-8h μm-level pattern PEG-20k 200 ppm


(a) NaCl Concentration profile along x axis
Smooth
Parallel
Bottom
Top
Transverse
mol/m³
NaCl Concentration profile along x axis
Smooth
Parallel-top
Parallel-bottom
Transverse
Concentration Polarization Degree
x axis (μm)
(b) PEG-400 Concentration profile along x axis
mmol/m³
PEG-400 Concentration profile along x axis
(c) PEG-20000 Concentration profile along x axis
mmol/m³
PEG-20000 Concentration profile along x axis


(a)
CPD for μm-level pattern
Smooth
Parallel
Transverse
Average concentration polarization degree
NaCl
PEG-400
PEG-20000
(b)
CPD with different viscosity parameters
Alpha (m³/mol)
(c)
CPD with different diffusion coefficients
Diffusion Coefficient (10⁻¹¹ m²/s)


(a)
PERO mm-level pattern NaCl
PERO 1
PERO 2
PERO 3
Observed Rejection (%)
smooth
parallel
transverse
(b)
PENF mm-level pattern PEG-400 200 ppm
PENF 1
PENF 2
PENF 1 rep
PENF 2 rep
(c)
PERO-48h mm-level pattern PEG-20k 200 ppm
PERO 1
PERO 2
PERO 1 rep
PERO 2 rep
(d)
PE mm-level pattern PEG-1M 200 ppm
PE 1
PE 2


(a)
CPD for mm-level pattern
Average concentration polarization degree
Smooth
Parallel
Transverse
NaCl
PEG-400
PEG-20000
PEG-1M
(b)
Solute: 2000 ppm NaCl
Average concentration polarization degree
Smooth
Parallel
Transverse
Pattern height (μm)
(c)
Solute: 200 ppm PEG-20000
Average concentration polarization degree
Smooth
Parallel
Transverse
Pattern height (μm)


(a)
PERO-Teflon mm-level pattern NaCl
Observed Rejection (%)
PENF 1
PENF 2
PENF 1 rep
PENF 2 rep
parallel
transverse
(b)
PENF-Teflon mm-level pattern Na2SO4
Observed Rejection (%)
PENF 1
PENF 2
PENF 1 rep
PENF 2 rep
parallel
transverse
(c)
PENF-2h-Teflon mm-level pattern PEG-600 200 ppm
Observed Rejection (%)
PENF 1
PENF 2
PENF 1 rep
PENF 2 rep
parallel
transverse