PaInT

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Forward osmosis under pressure: Performances and challenges of pressure assisted osmosis (PAO)

Never Stand Still | Faculty of Engineering | School of Chemical Engineering

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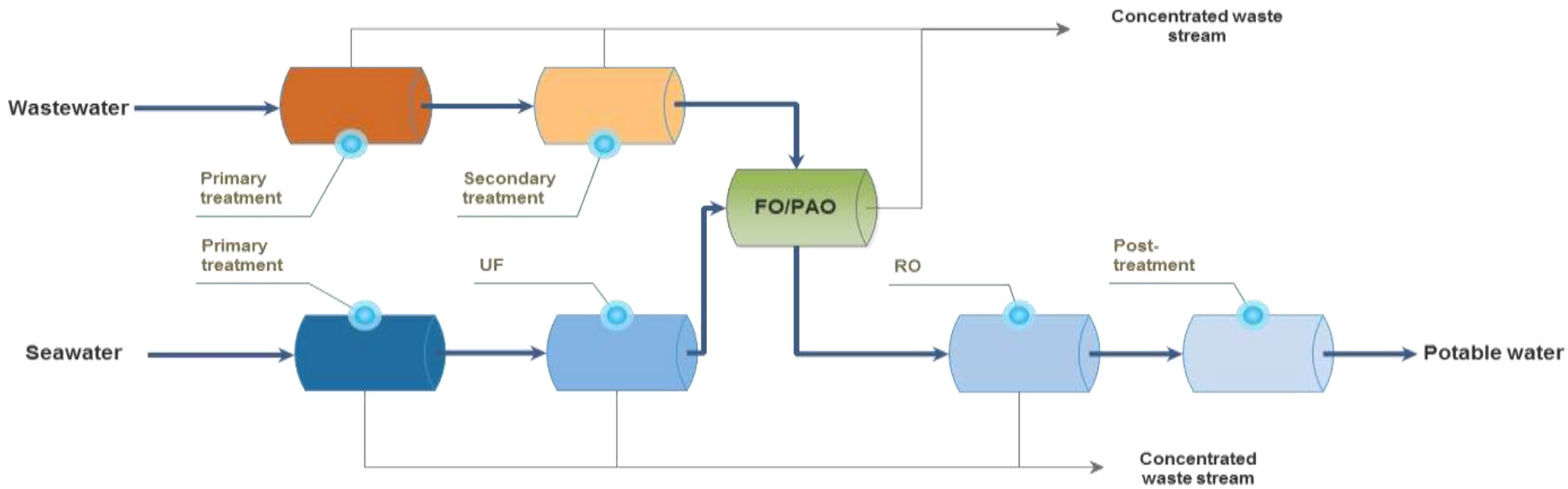
Outlook

- FO-RO hybrid concept in desalination pre-dilution
- Assessment of three commercial membranes performances in FO and PAO operation:
  - Membrane characteristics and deformation
  - Water and solute mass transfer
  - Fouling
  - Trace organic contaminants rejection (not discussed today)
- Energy, capital cost model
- Practical challenges (module and pressure drop)
- New concept of PAO-NF

FO-RO hybrid: Seawater pre-dilution



First study: Cath et al. [1,2]

- Lower energy for seawater desalination thanks to the osmotic dilution
- Beneficial reuse of wastewater, i.e. water recycling
- Multi-barrier protection to increase consumer confidence in water recycling
- Reduction in reverse osmosis membrane fouling

Promising but need for flux improvement

1 Cath, T. Y. et al. (2009). "A Novel Hybrid Forward Osmosis Process for Drinking Water Augmentation using Impaired Water and Saline Water Sources." WERC.
2 Cath, T. Y. et al. (2010) Journal of Membrane Science **362(1–2): 417-426.**

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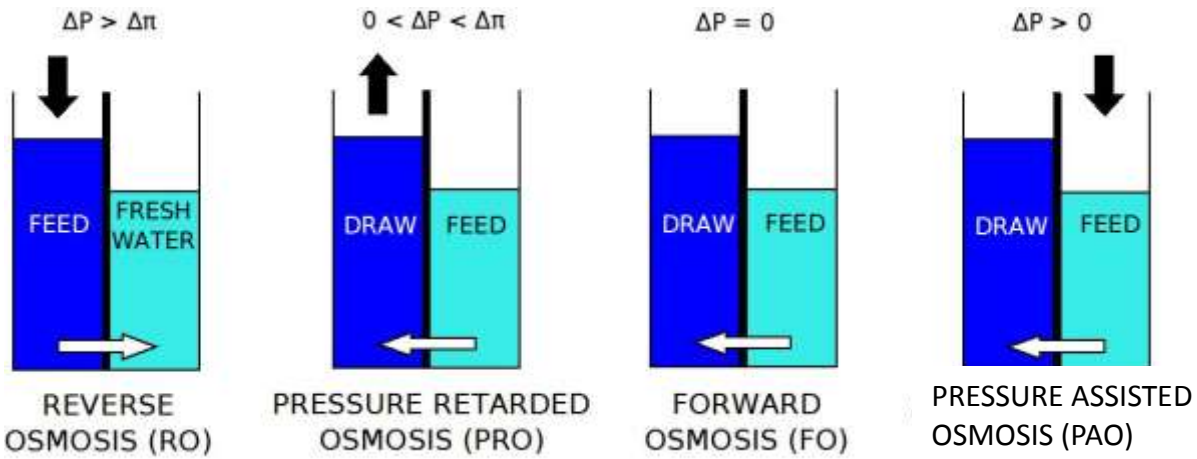
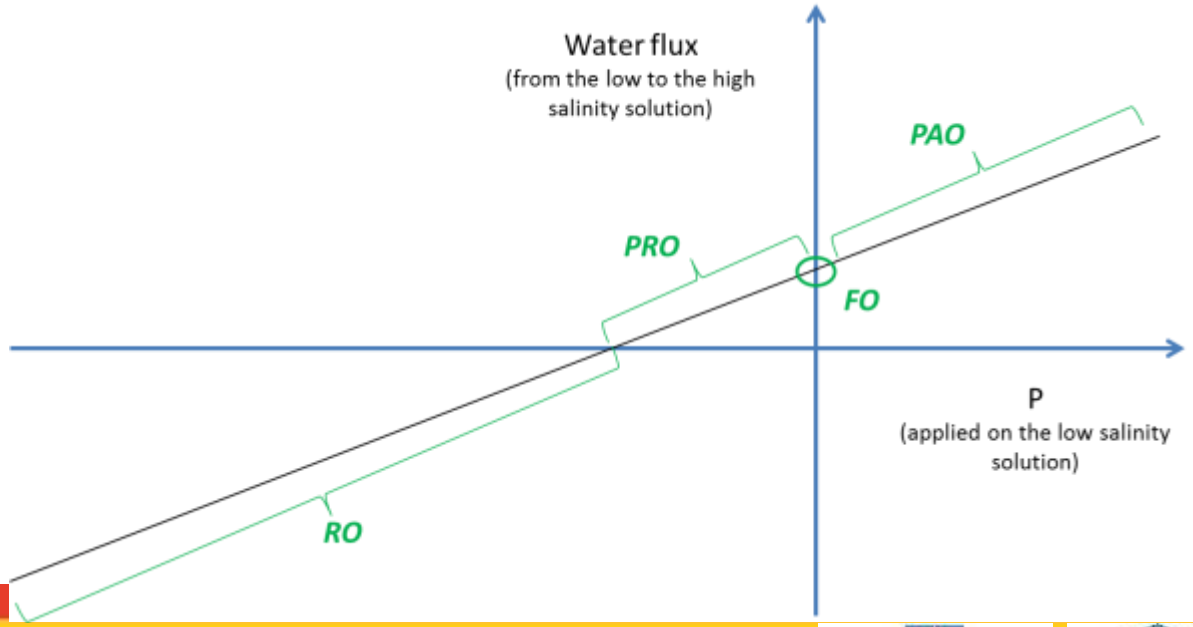
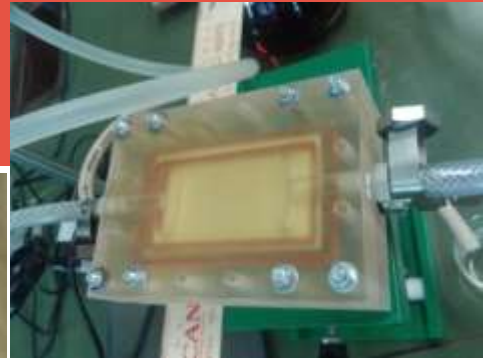
Osmotic processes

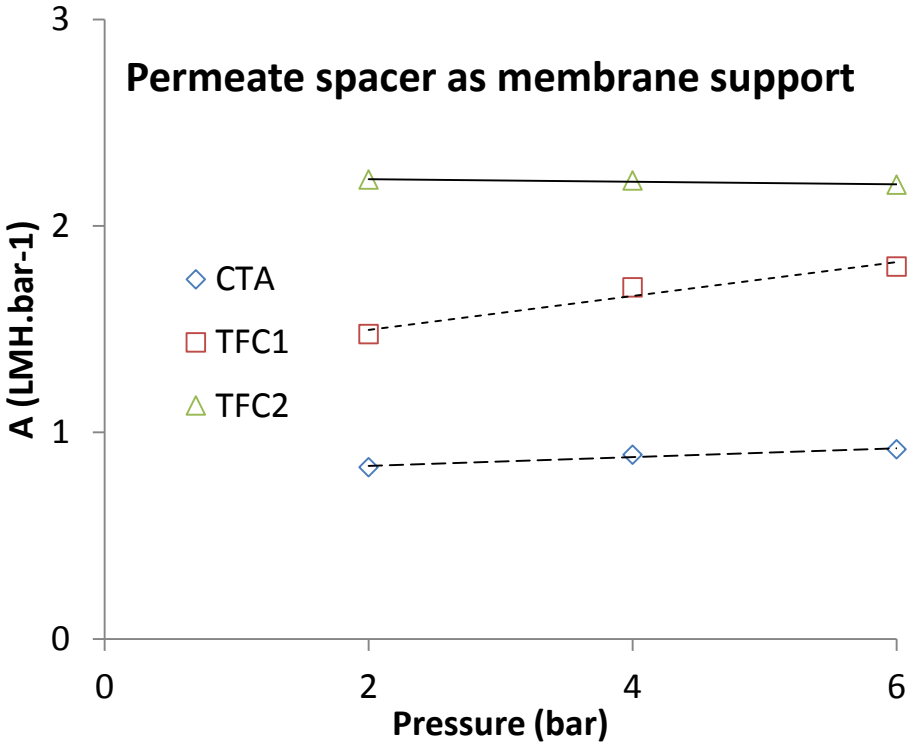


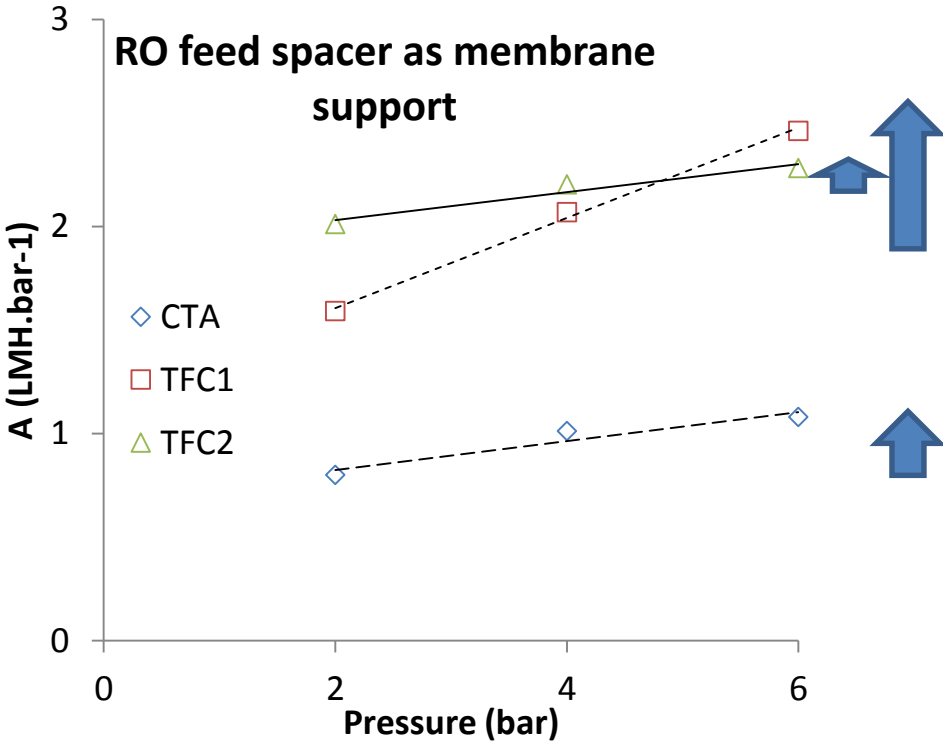


Membrane characteristics under pressure

Water permeability: effect of the SPACER (in RO cross flow setup)







Improved permeability with TFC membranes

FO membrane deformation with pressure when RO feed spacer is used!

Blandin et al. (2013) Journal of Membrane Science

Membrane characteristics

Salt permeability (RO cross flow setup)

	A ($L.m^{-2}.h^{-1}.bar^{-1}$)			B ($10^{-7}\cdot m.s^{-1}$)			B/A (0bar)	S_0
	0 bar	4 bar / permeate spacer	4 bar / RO feed spacer	0 bar	4 bar / permeate spacer	4 bar / RO feed spacer		µm
CTA, HTI	0.7	0.9	1.0	1.5	2.1	3.1	2.1	663
TFC1, HTI	1.3	1.7	2.1	0.3	0.6	0.7	0.23	1227
TFC2, Porifera	2.1	2.2	2.2	1.2	1.4	1.4	0.57	344

Membrane deformation also increases Salt permeability (B)

Improved selectivity with TFC membranes

High variation on S values!

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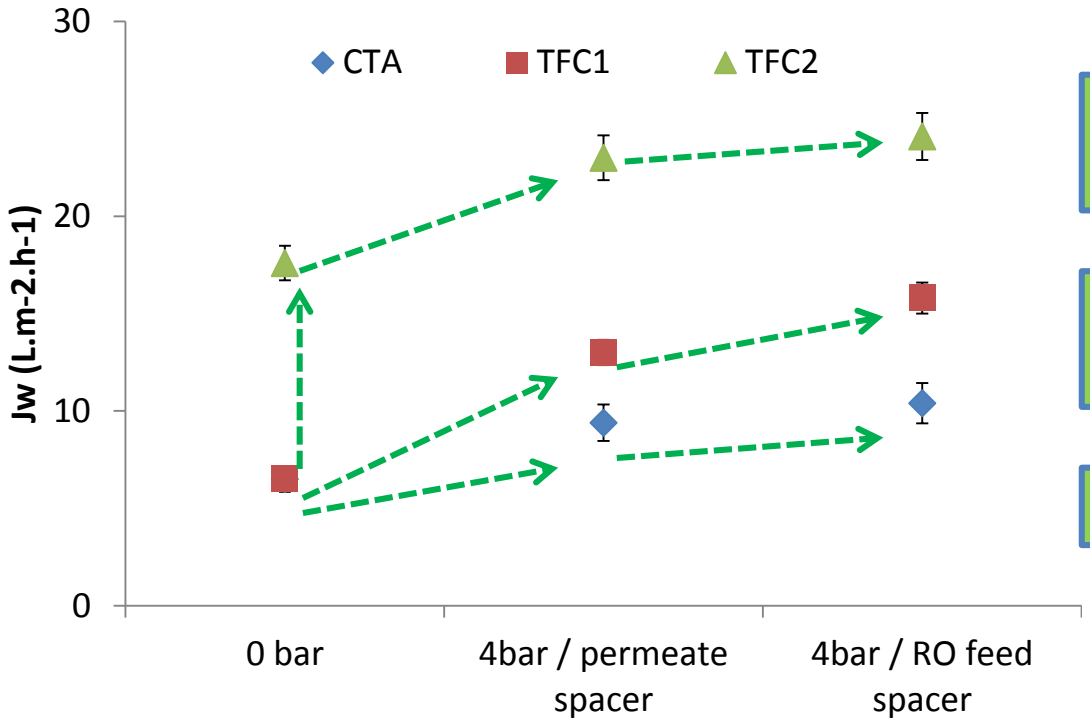
Experimental vs. modelled water flux

DI as feed, 35g.L^{-1} red sea salt as draw



FO: 2 times higher flux with TFC2! (lower S value)

PAO: Pressure increases flux in all cases

Deformation further improved flux

Both novel membrane development and hydraulic pressure (PAO) help to improve water flux

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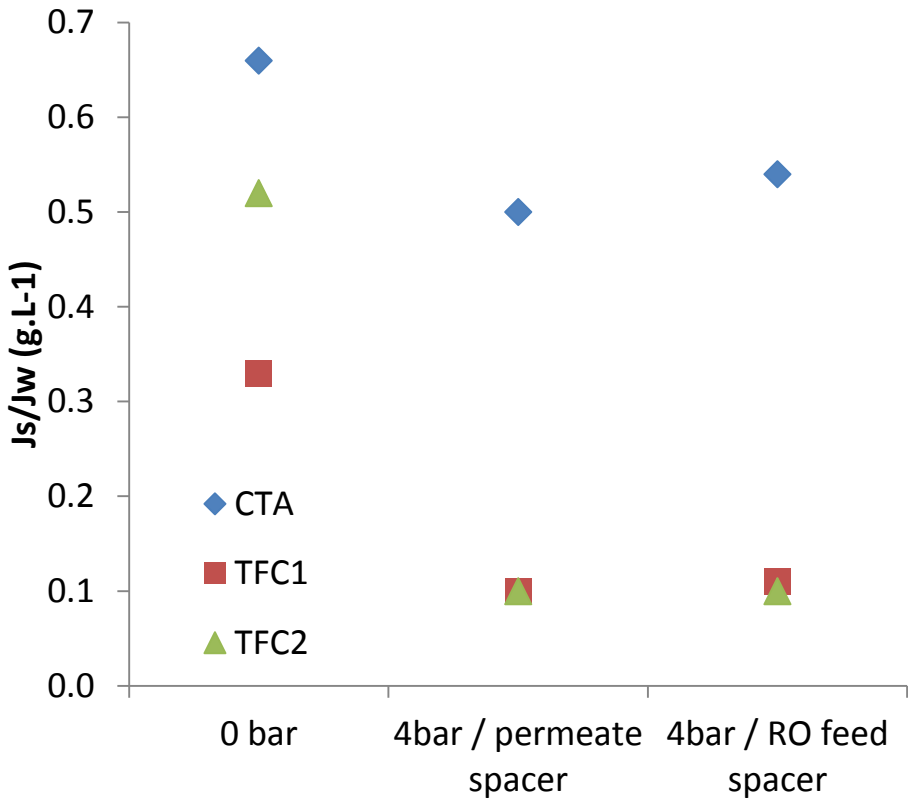
Reverse salt diffusion

DI as feed, 35g.L^{-1} red sea salt as draw



PAO: decrease of RSD for all membranes

- Despite deformation/ stretching
- Thanks to more severe ICP resulting of pressure-enhanced water flux!

PAO operation allows to tackle the water/salt permeability trade off of FO!!

- Higher water permeability
- Lower reverse salt diffusion

Potential interest in using more permeable membrane in PAO even with lower salt rejection!

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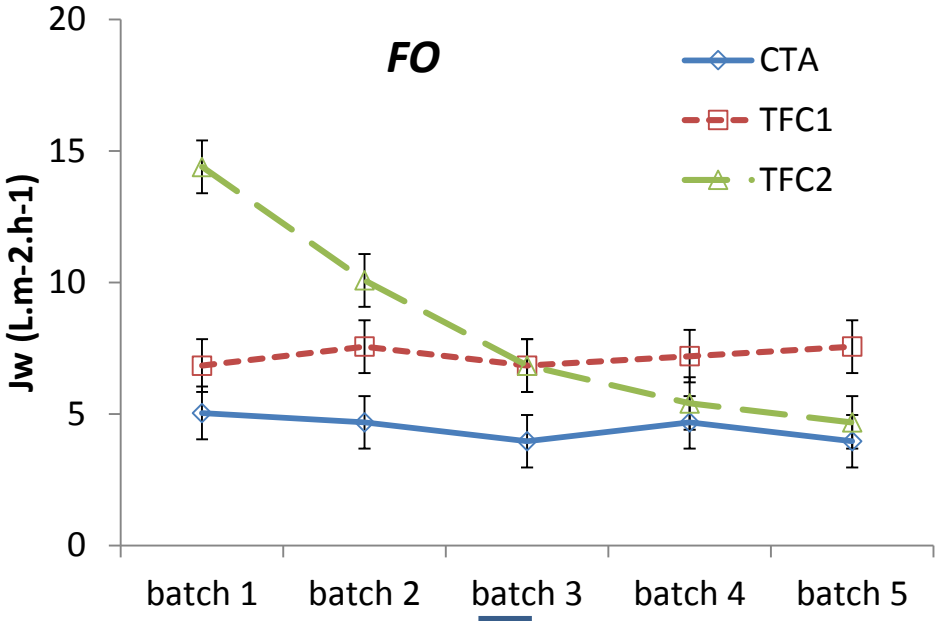
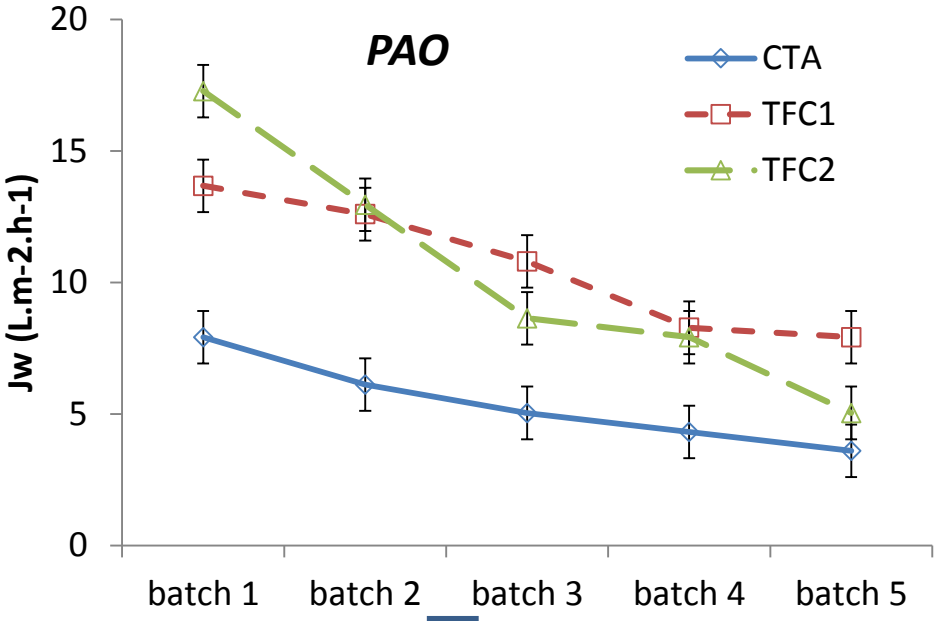
Fouling behaviour

Foulant mix: 1.2g/L Sea salts, 200mg/L CaCl2, 200mg/L Alginate, 200mg/L Humic acid
Five (5) consecutive batches at constant recovery =30%





Lower flux membranes: no flux decline
More severe flux decline with high flux Porifera P

Performance decrease observed with all 3 membranes in PAO mode!

Is fouling due to higher operating flux?

Is fouling due to applied pressure or higher operating flux?

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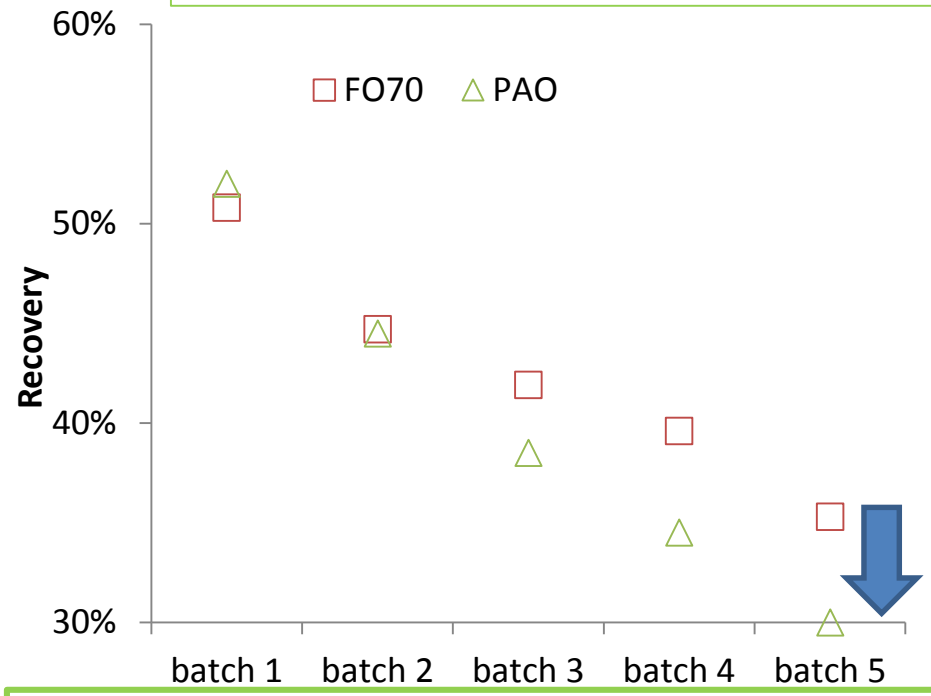
Fouling behaviour

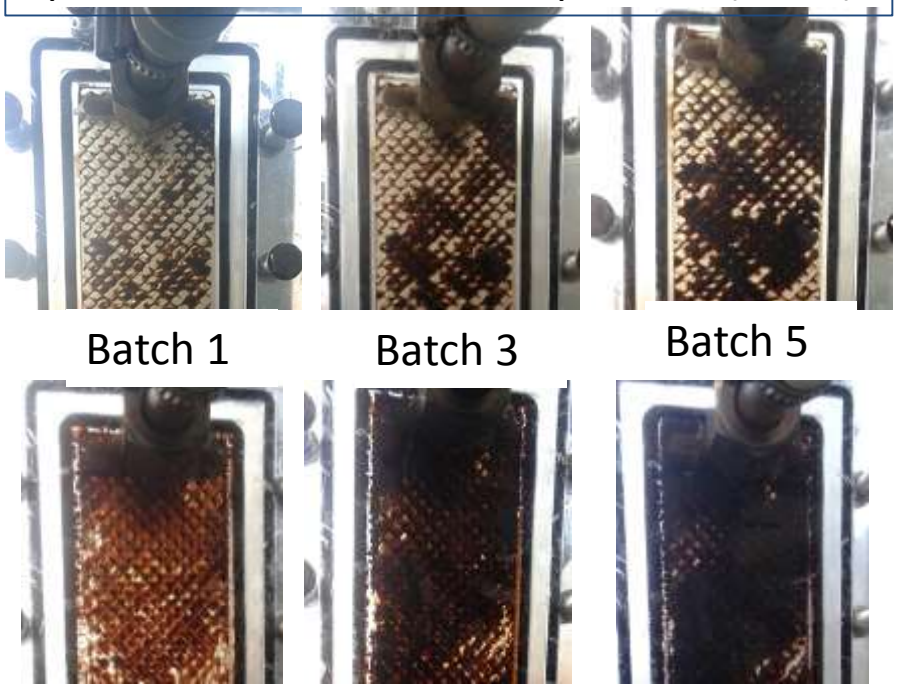
Impact of hydraulic pressure

CTA, AL-FS



More severe loss of recovery when hydraulic pressure is implemented!

Sparse and smooth cake deposition (FO70)



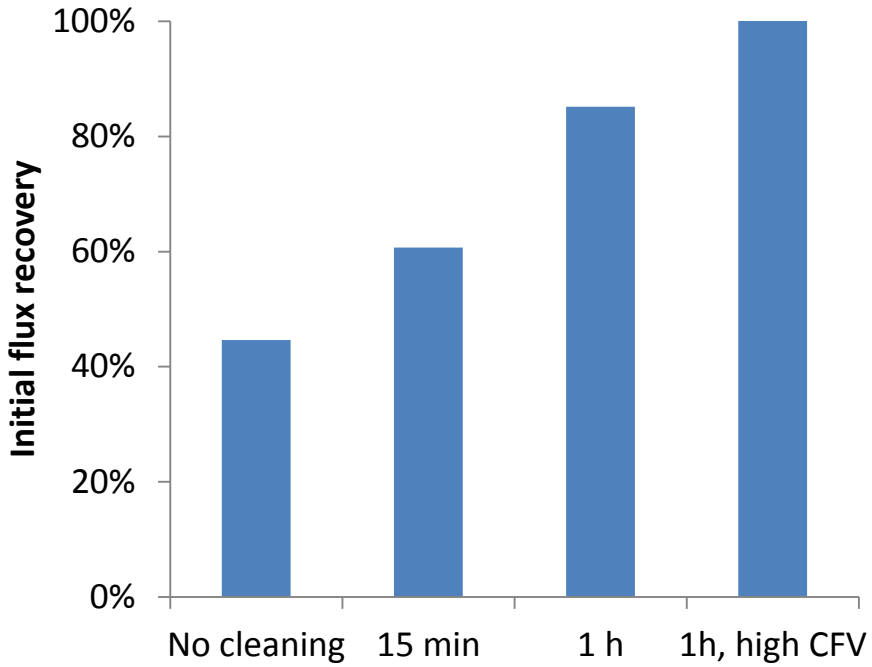
Formation of a layer on the membrane and then accumulation (PAO)

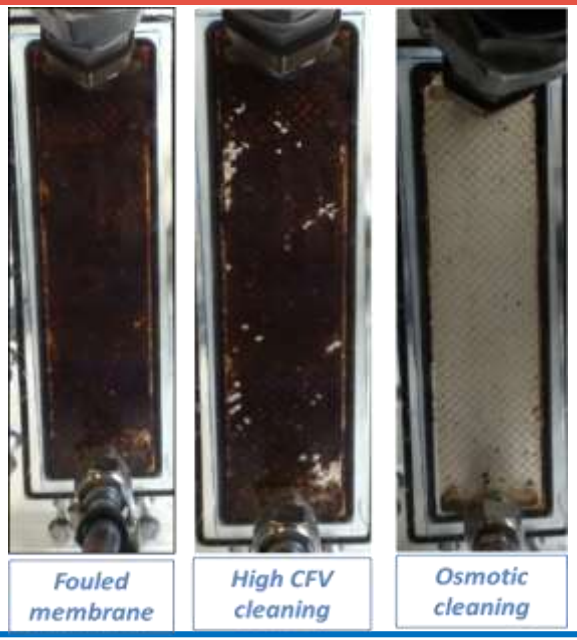
Confirms higher fouling behaviour with PAO
Different foulant cake structure (compaction!)

More on: "Is FO really a low fouling process"
Poster IDA-51730

Cleaning strategy for high flux fouling

FO, TFC2, AL-FS





Possible to recover initial flux with extended time of osmotic backwashing at high CFV

Osmotic cleaning also adapted to operation of FO with high permeation flux!

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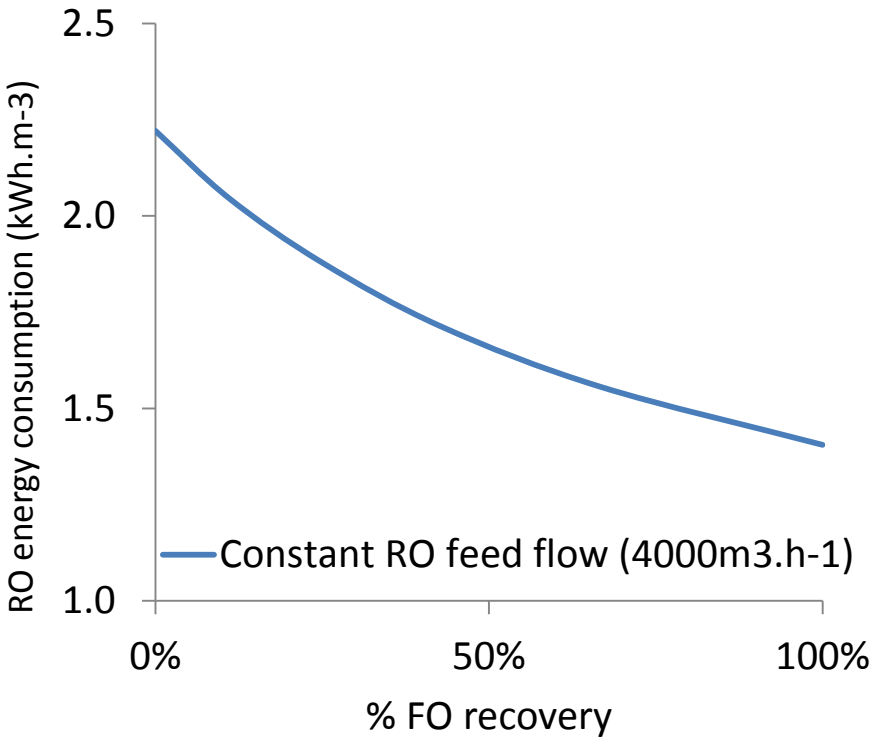
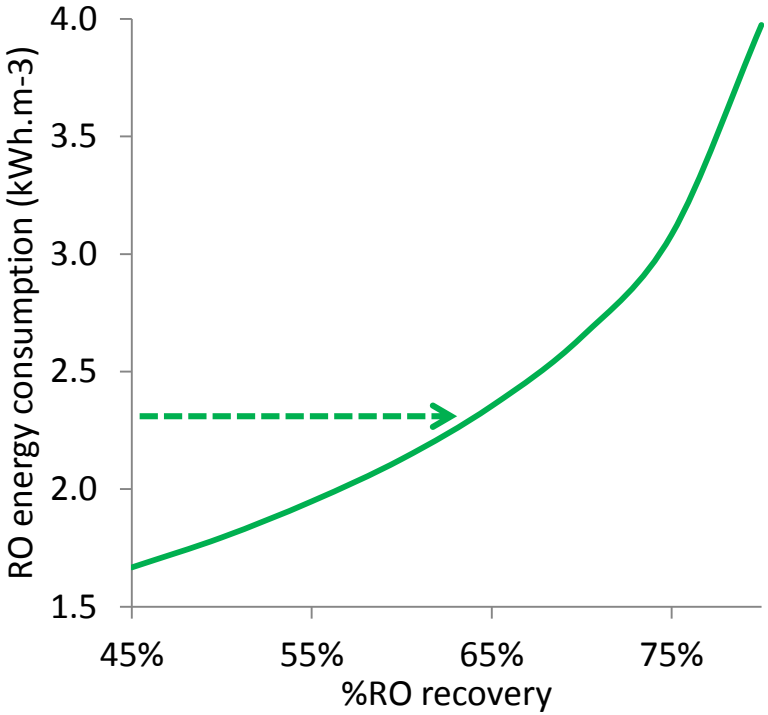
Impact of FO recovery on RO energy consumption

How to use the osmotic dilution?

Scenario A: Constant RO feed flow and RO recovery



Scenario B: Constant RO feed flow (diluted by pre-FO) and increased RO recovery



Possible to reduce by 30% RO energy needs
or to increase RO recovery up to 60-65% for similar energy consumption

RO energy consumption considering different scenario of FO-RO hybrid implementations using ROSA software.
Blandin et al. (2015). Desalination **363: 26-36**

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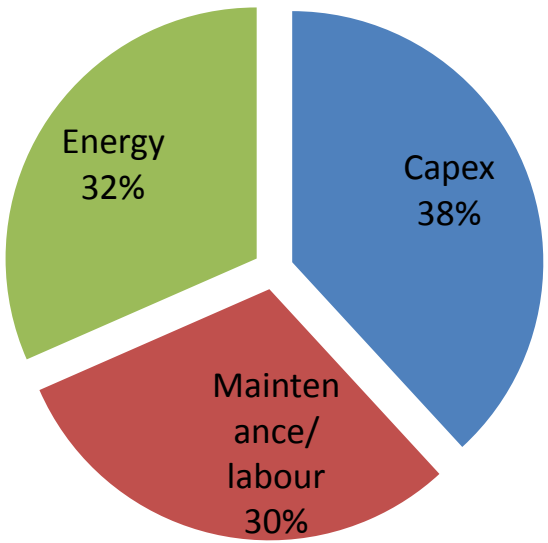
SWRO desalination economics

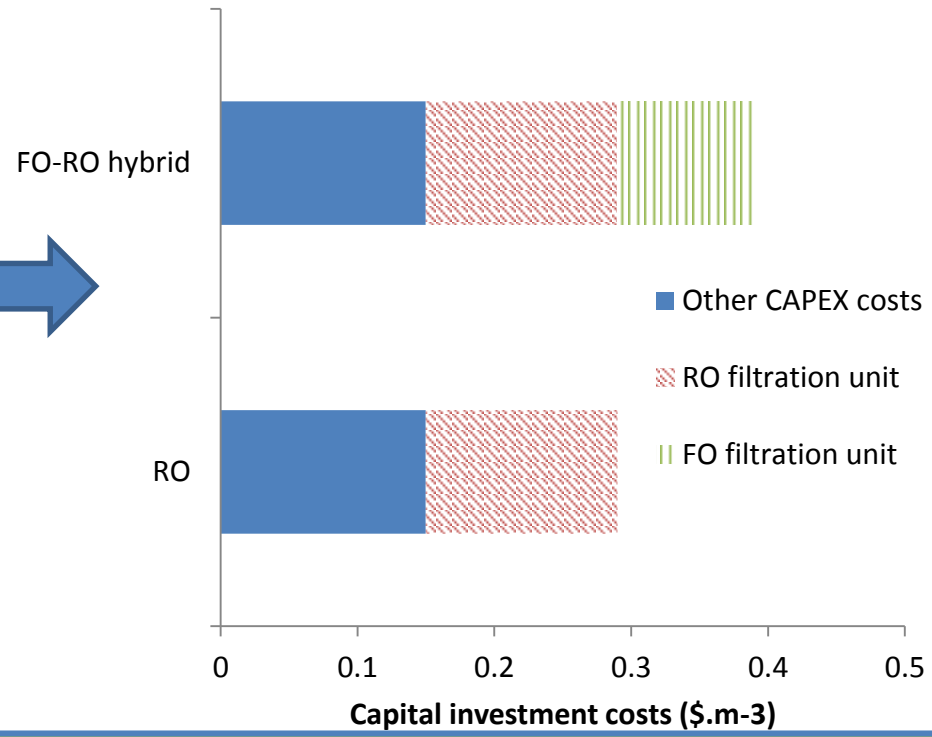
FO/PAO-RO hybrid can allow for lower energy needs (30%) and possible lower maintenance costs. But…

Average water production cost: 0.76$.m^{-3}



Desaldata.com

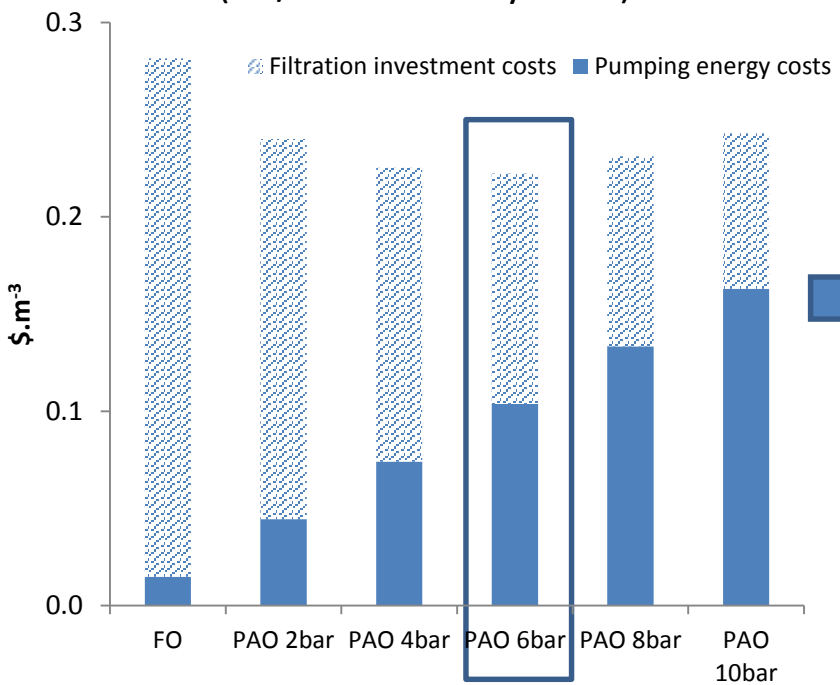
If similar flux in FO/PAO and RO!



Important to consider investment cost in FO/PAO-RO hybrid economics!

FO vs. PAO
CAPEX vs. energy?

Model based on HTI CTA membrane
(FO/PAO recovery=50%)



PAO is beneficial vs. FO thanks to a significant decrease of filtration costs

Optimum of operation
(6bar for HTI CTA membrane, and economics assumptions considered)

Despite higher energy need, PAO could be more financially attractive than FO

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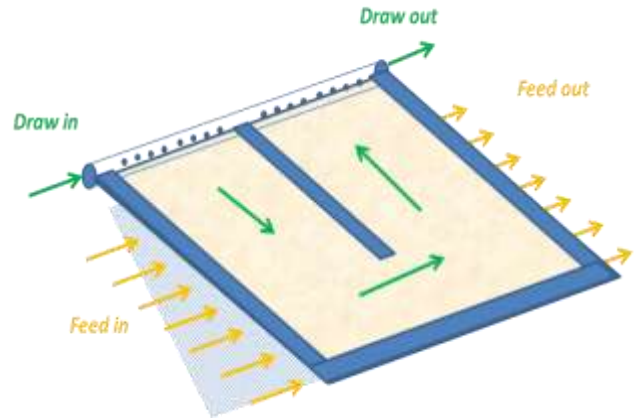
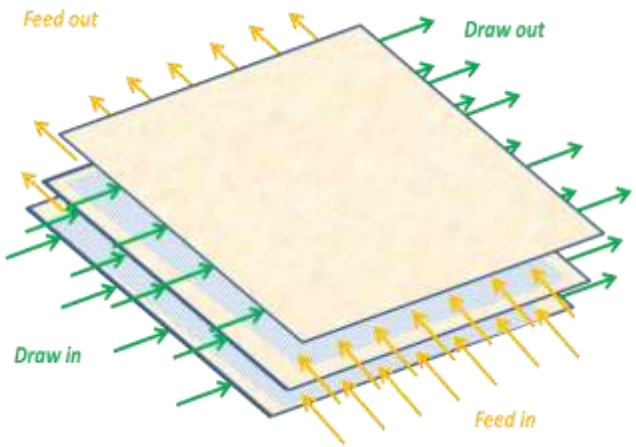
FO Module operation

Development/commercialisation: Spiral wound, plate and frame and hollow fibre configurations





Difference with RO:
Need to circulate both feed and draw solutions

Challenges in design

- Packing density
- Optimised hydraulics
- Membrane support

Pressurisation will be needed for feed/draw transfer (PAO operation could not be avoided)

Further work needed to understand feed/draw hydraulics optimisation and interconnections!

http://www.globalwaterintel.com/news/2013/45/toray-boosts-membrane-market-share-woongjin-buy.html
http://porifera.com/products/pfo-modules-systems/
http://www.toyobo-global.com/news/pdf/2014/05/press20140521.pdf

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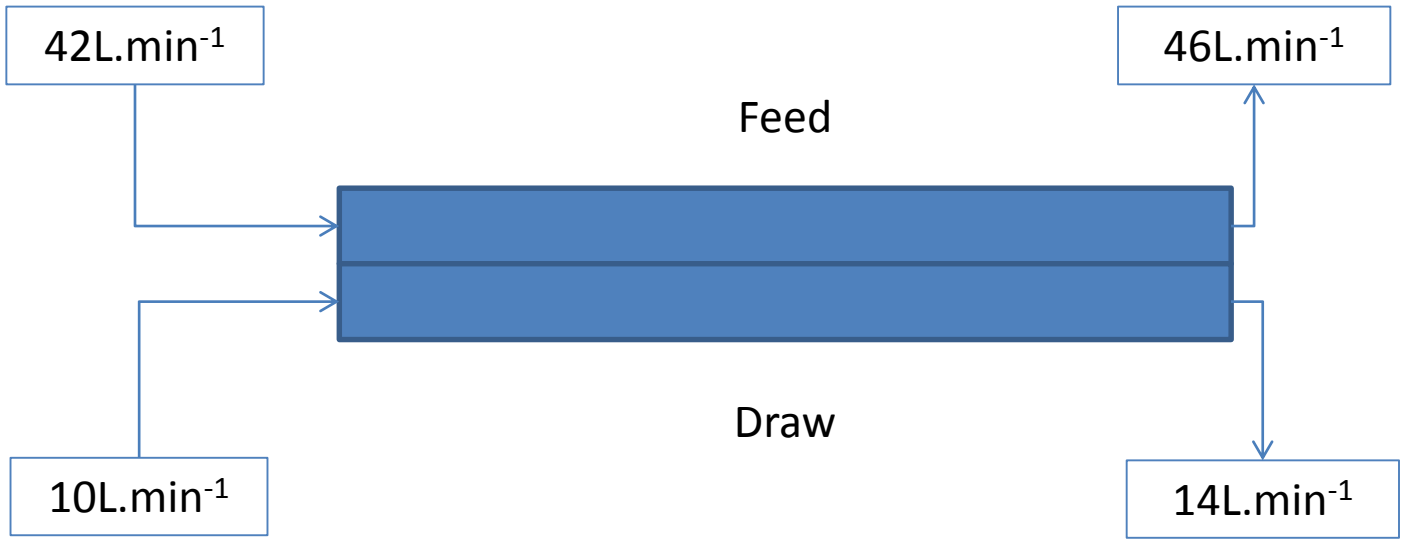
Hydrodynamics in 8” module (from initial pilot testing)

Typical FO operation



Volume Increase by 40% in one pass in the module!!
Slight pressure build up in draw channel!

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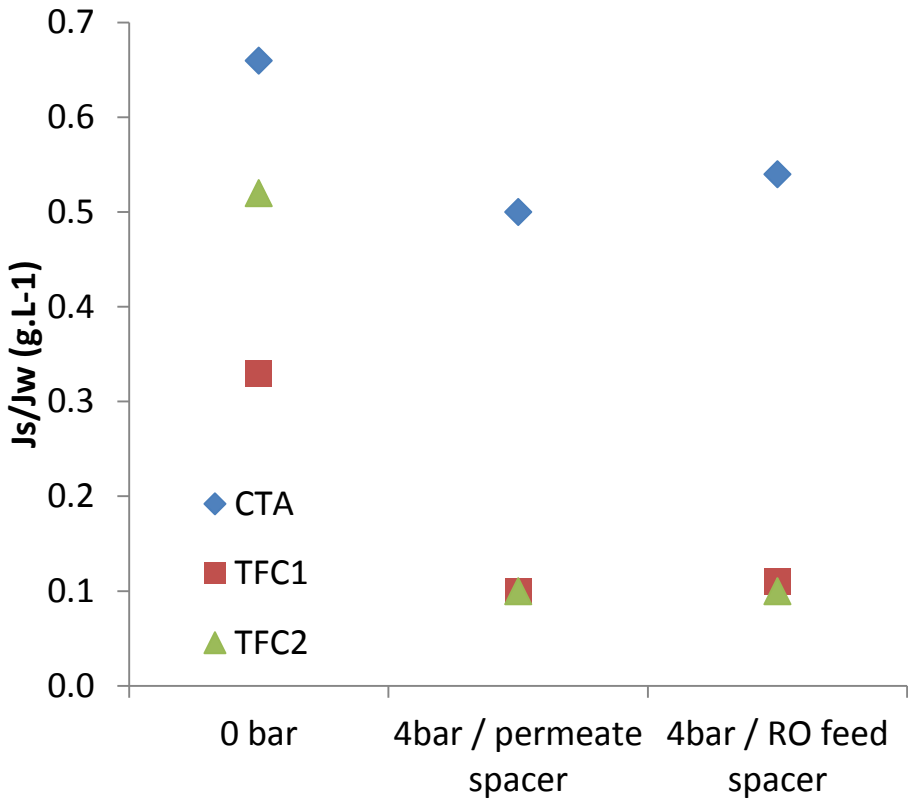
Reverse salt diffusion

DI as feed, 35g.L^{-1} red sea salt as draw



PAO: decrease of RSD for all membranes

- Despite deformation/ stretching
- Thanks to more severe ICP resulting of pressure-enhanced water flux!

PAO operation allows to tackle the water/salt permeability trade off of FO!!

- Higher water permeability
- Lower reverse salt diffusion

Potential interest in using more permeable membrane in PAO even with lower salt rejection!

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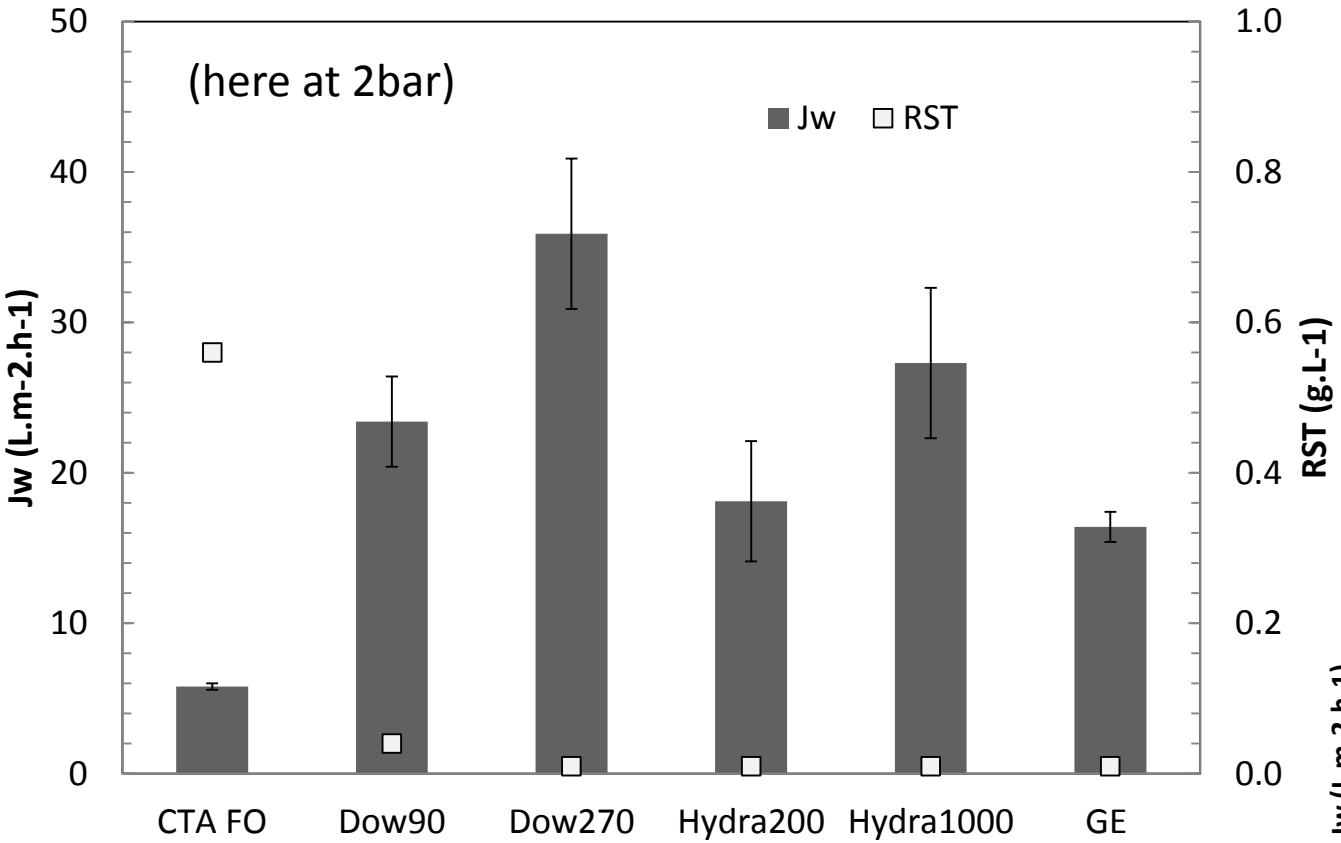
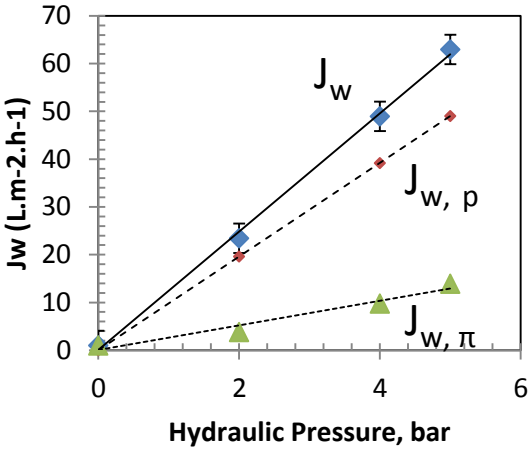
The concept of PAO-NF





Small contribution of osmotic pressure
Higher fouling rate, but easily reversible
But option to consider when high flux is needed

More on that Wednesday 2pm
VALIDATION OF PAO-NF CONCEPT
IDA #51503

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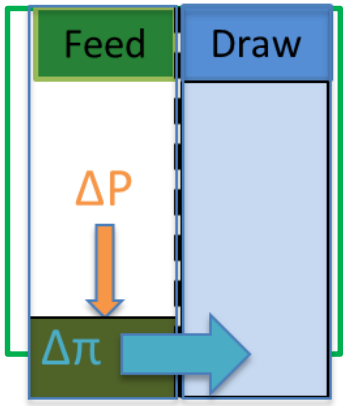
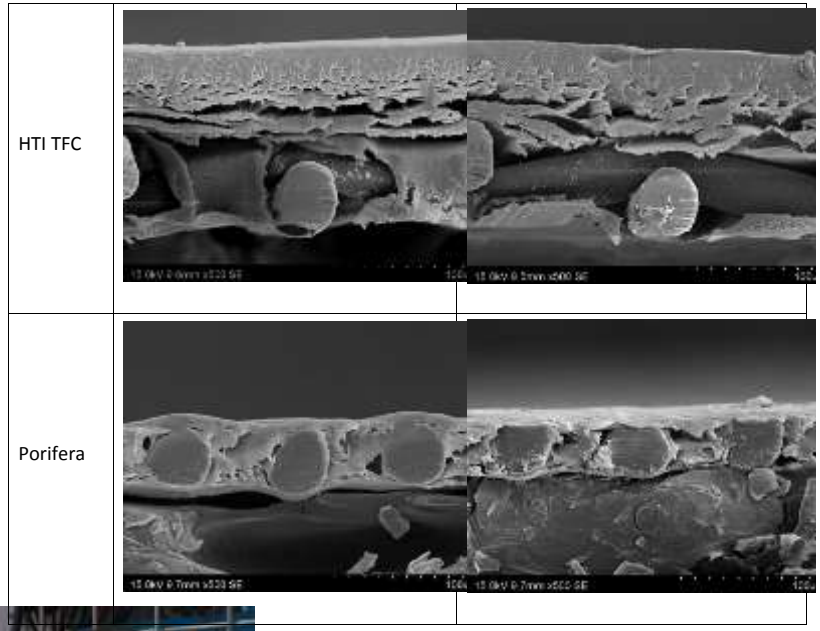
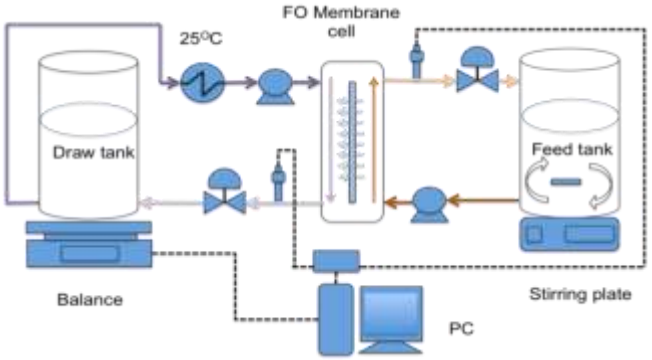
Thanks!

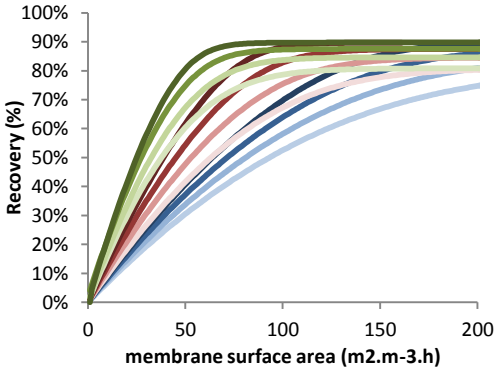
Questions ?

PAO









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