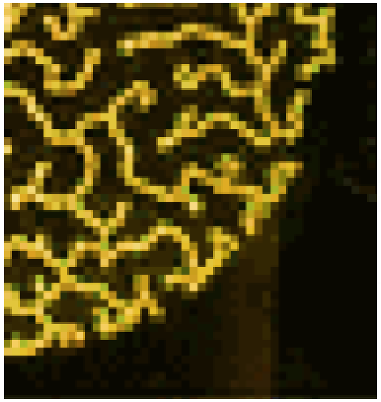


PoreLab

Senter for fremragende forskning

NTNU-UiO Porous Media Laboratory

Water and power production from industrial waste heat using nanoporous membranes

Signe Kjelstrup[1], Luuc Keulen[2], Norbert Kuipers[3]

[1]PoreLab, Department of Chemistry, Norwegian University of Technology and Science

[2]Department of Aerospace Science and Technology, Politecnico di Milano, Italy

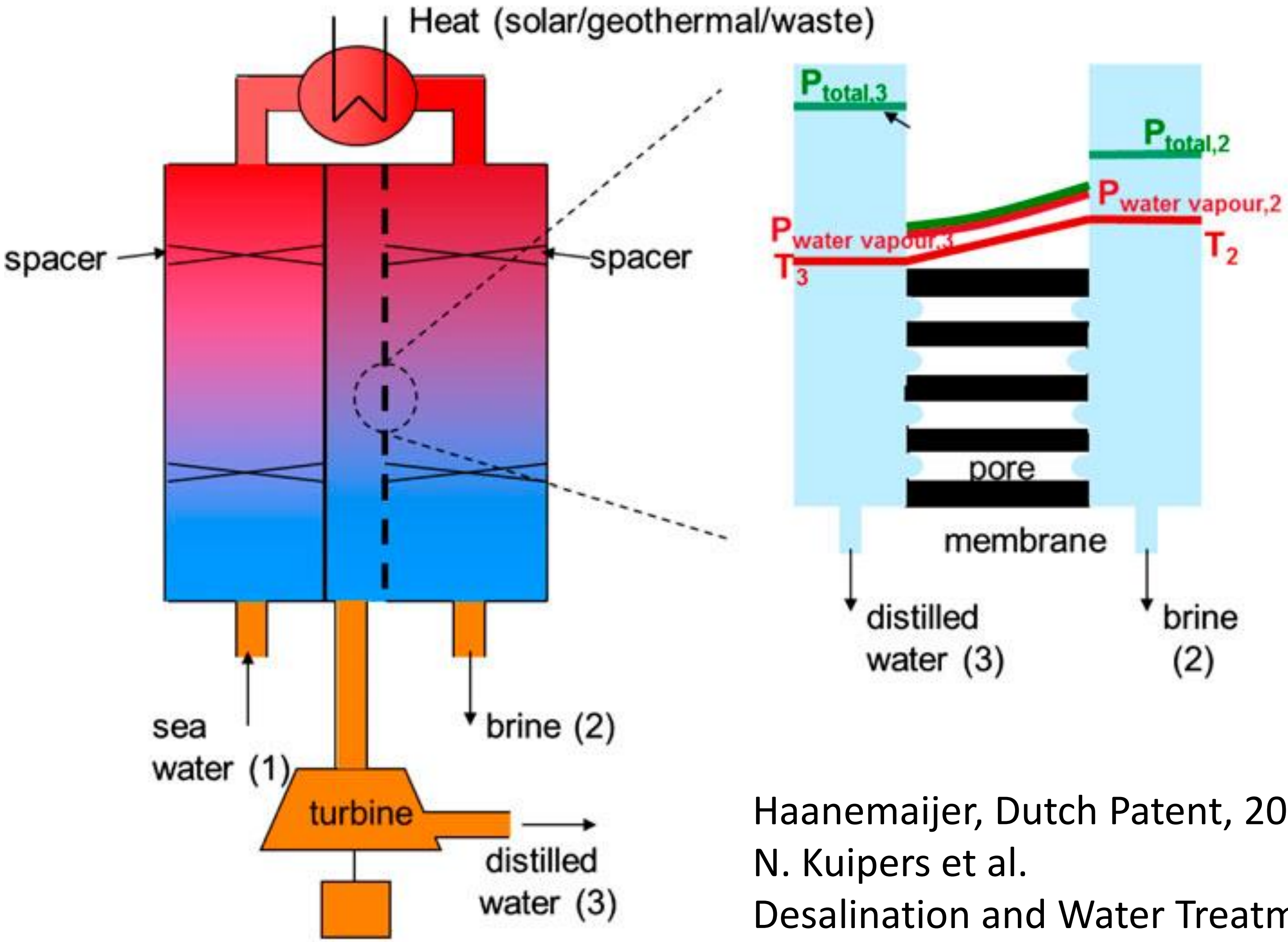
[3]Department of Water Treatment, Netherlands Organisation for Applied Scientific Research, TNO, 3704HE Zeist, The Netherlands

Outline

- **The MemPower Concept**
- **Coupled transport of heat and mass**
- **Overall transfer coefficients**
- **Predictions for water and power production**

L. Keulen, van der Ham, N. Kuipers, J.H. Haanemaijer, T. Vlugt, S. Kjelstrup, J. Membr. Sci (2016)
L. Keulen, N. Kuipers, S. Kjelstrup, in progress

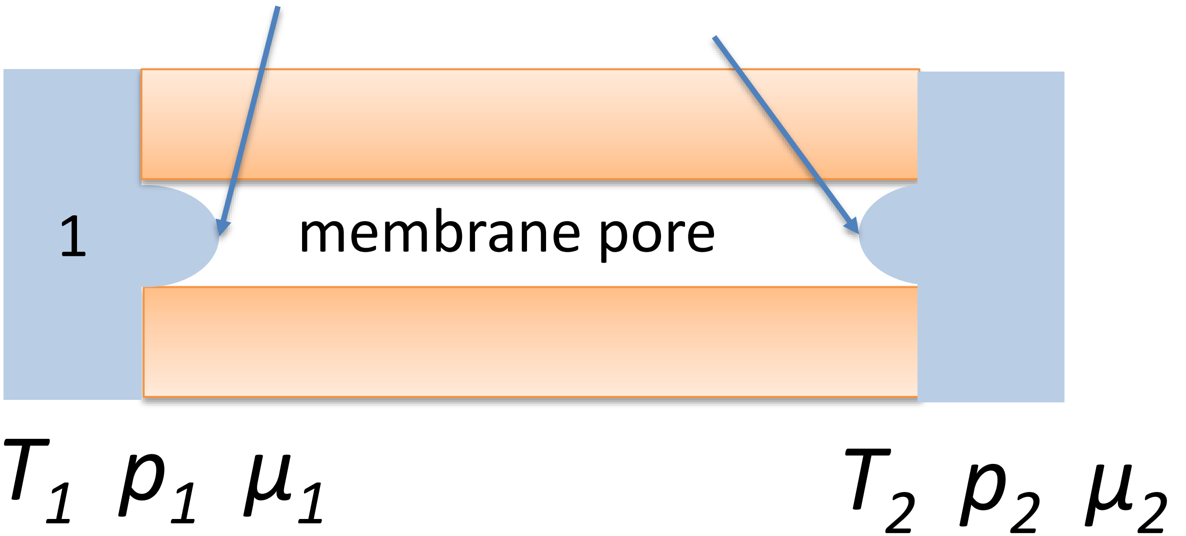
The MemPower Concept

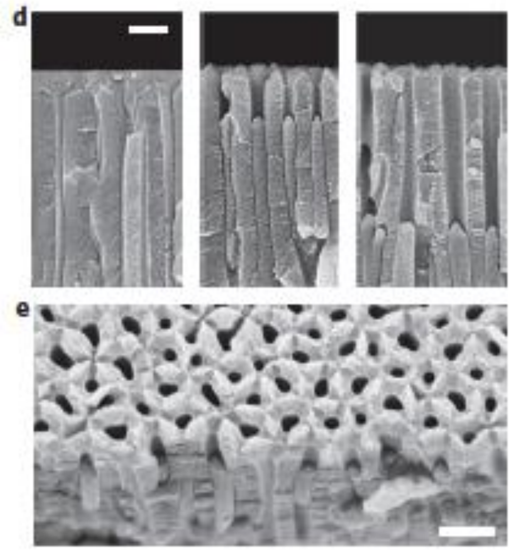


Haanemaijer, Dutch Patent, 2013
N. Kuipers et al.
Desalination and Water Treatment, 2014

Heat and water transfer..

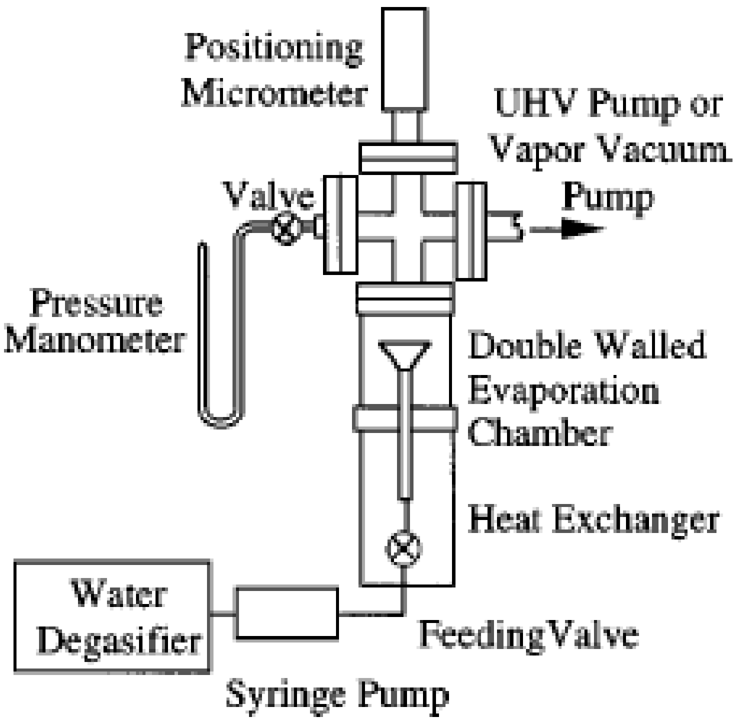
across interfaces and hydrophobic nanopores

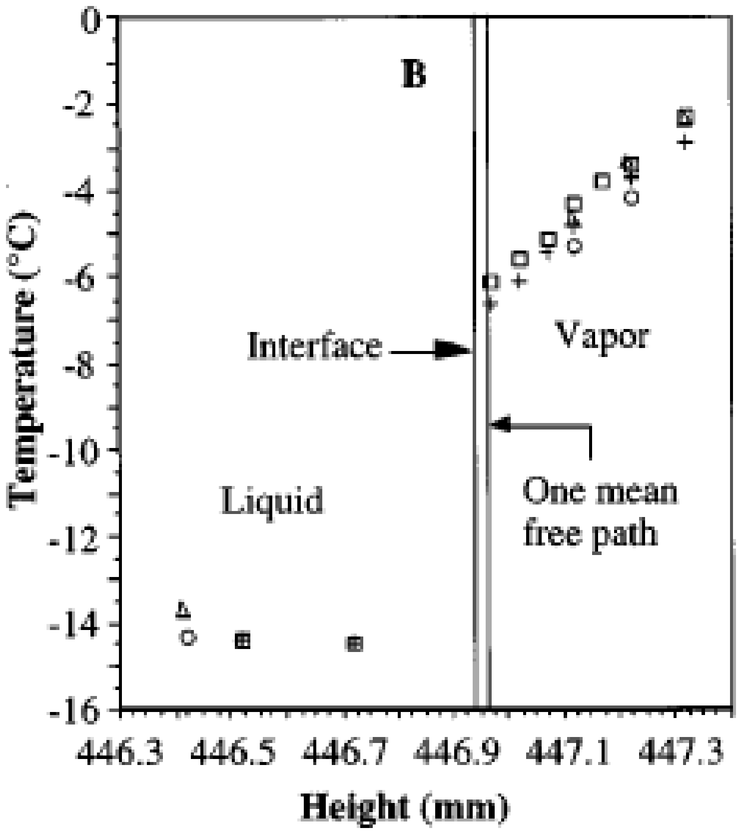




Lee et al. Nature Nanotechnology, 2014

Interface resistance: Evaporation of water





Ward, Fang, Phys. Rev. E 59 (1999) 417

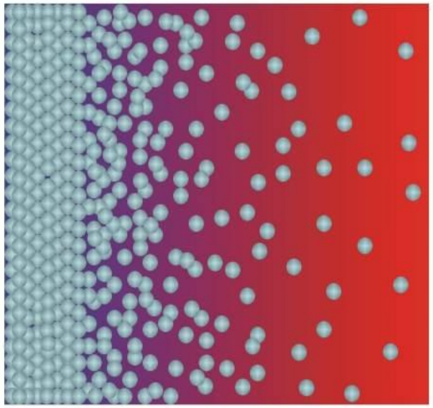
Entropy production for the liquid - vapor interface

Stationary state $J^{l} = J^{g} = J, \qquad J_q^{'l} - J_q^{'g} = J\Delta_{\text{vap}}H$

$$\sigma^{s} = J_q^{'l}\left(\frac{1}{T^{o}} - \frac{1}{T^{l}}\right) - J\left(\frac{\mu^{g} - \mu^{l}(T^{g})}{T^{g}}\right)$$

=

$$\text{R}\ln p / p^{*}$$



Defines constitutive equations.....

Interface flux-force relations

Two driving forces and their conjugate fluxes, at each interface

$$\frac{1}{T^g} - \frac{1}{T^l} = r_{qq} J_q^{'l} + r_{qm} J$$

$$-\frac{\mu^g - \mu^l (T^g)}{T^g} = r_{mq} J_q^{'l} + r_{mm} J$$

- Symmetric matrix of coefficients (Onsager)
- Schrage’s formula, Statistical rate theory, Kinetic theory contained

The model obeys the entropy balance in each part of the system

Overall resistance = sum for 2 interfaces and 3 bulk phases

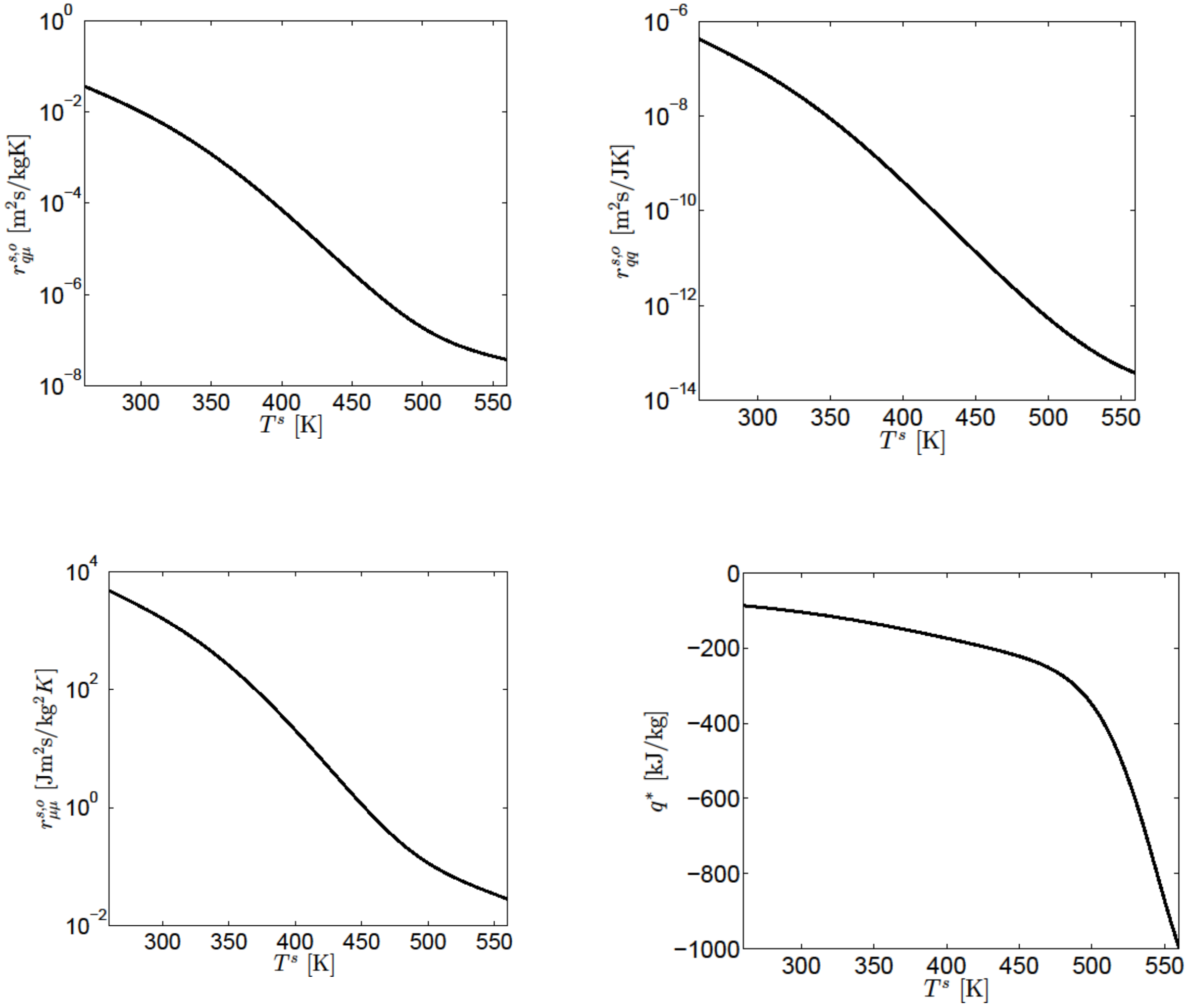
$$\frac{1}{T_2} - \frac{1}{T_1} = r_{\text{qq}}^{\text{tot}} J'_{q,2} + r_{\text{qw}}^{\text{tot}} J_w$$

$$-\frac{\mu_2^l - \mu_1^l(T_1)}{T_1} = r_{\text{wq}}^{\text{tot}} J'_{q,2} + r_{\text{ww}}^{\text{tot}} J_w$$

Contributions to the total resistance are estimated from

1. Liquid water properties - water boundary layers
2. Kinetic theory – gas in pore
3. Interface coefficients, flat surfaces, Wilhelmsen et al. 2015

Interface transfer coefficients for water, flat interface



Wilhelmsen et al.
PRE, 2015

NTNU

State-of-the art modelling

Difference in vapor pressure due to difference in *T*

Water flux in membrane pore

$$J_w = -\varepsilon B \frac{\Delta P_w^*}{d_{mem}}$$

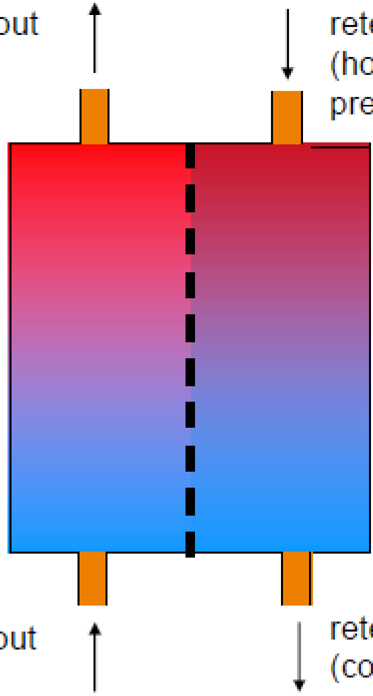
Heat flux on the permeate side

$$J_{q,2} = -\lambda \frac{\Delta T}{d_{mem}} + J_w \Delta H_{vap,w}$$

Does not obey coefficient symmetry. does not obey the entropy balance!

Khayet and Matsura, Membrane Distillation Principles and Application, Elsevier , 2011

Comparing with experimental results



Membrane Property	Value
Membrane thickness	$5.0\ 10^{-6}$ m
Pore diameter	$2.0\ 10^{-7}$ m
Porosity	0.8
Thermal conductivity	0.19 W/K m

Water flux:

Measured: (1 ± 1) 10^{-2} kg/m^2 s

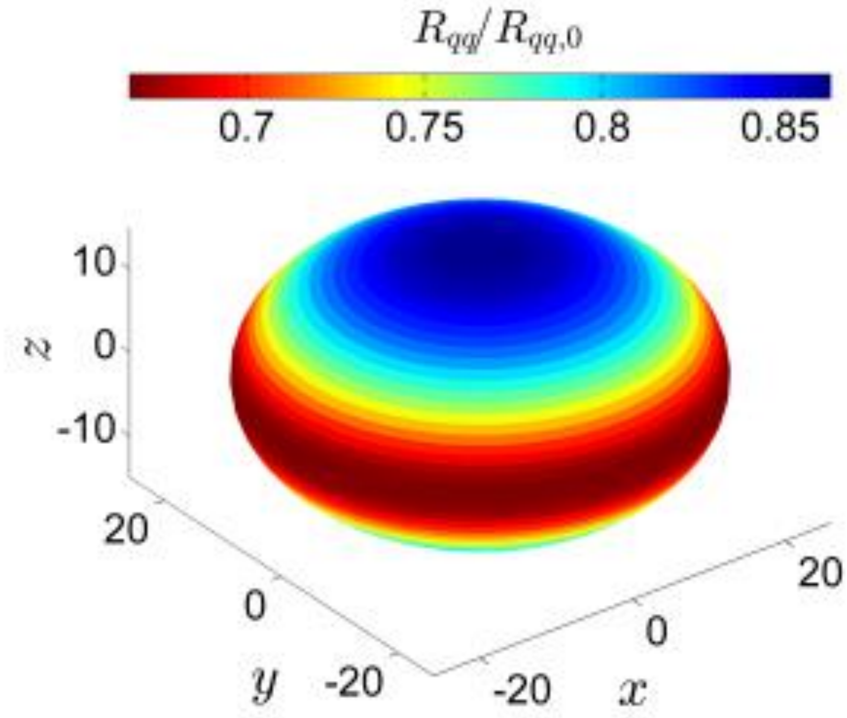
NET model: (1.1 ± 0.3) 10^{-3} kg/m^2 s

State of the art model: 2.2 kg/m^2 s

Average temperatures:
85.5 (p) and 46.0 ^{o}C (r)
Counter-pressure: 1.2 bar

Accuracy of NET- coefficients?

- Effect of curvature of Lennard-Jones particles on thermal resistivity

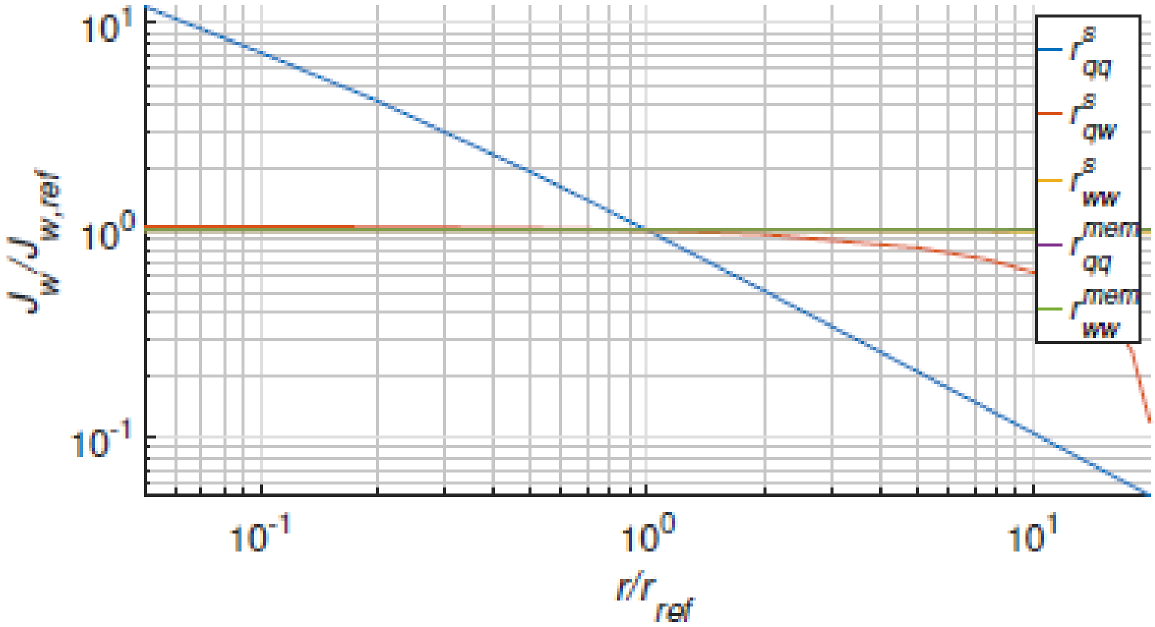


(a) Oblate Spheroidal droplet

Wilhelmsen et al.
J. Phys. Chem. C,
2015

Relative importance of interface resistivity

- Relative mass flux as a function of scaled coefficient



13

NTNU

Predicting the thermo-osmotic pressure:

- Soret equilibrium across the membrane:
  A pressure difference will stop the water flux

Same solutions on the two sides:

$$-\frac{\Delta T}{T_1 T_2} = r_{\mathrm{qq}}^{\mathrm{tot}} J_{q,2}^{'}$$

$$-V_w \Delta p = r_{\mathrm{wq}}^{\mathrm{tot}} J_{q,2}^{'}$$

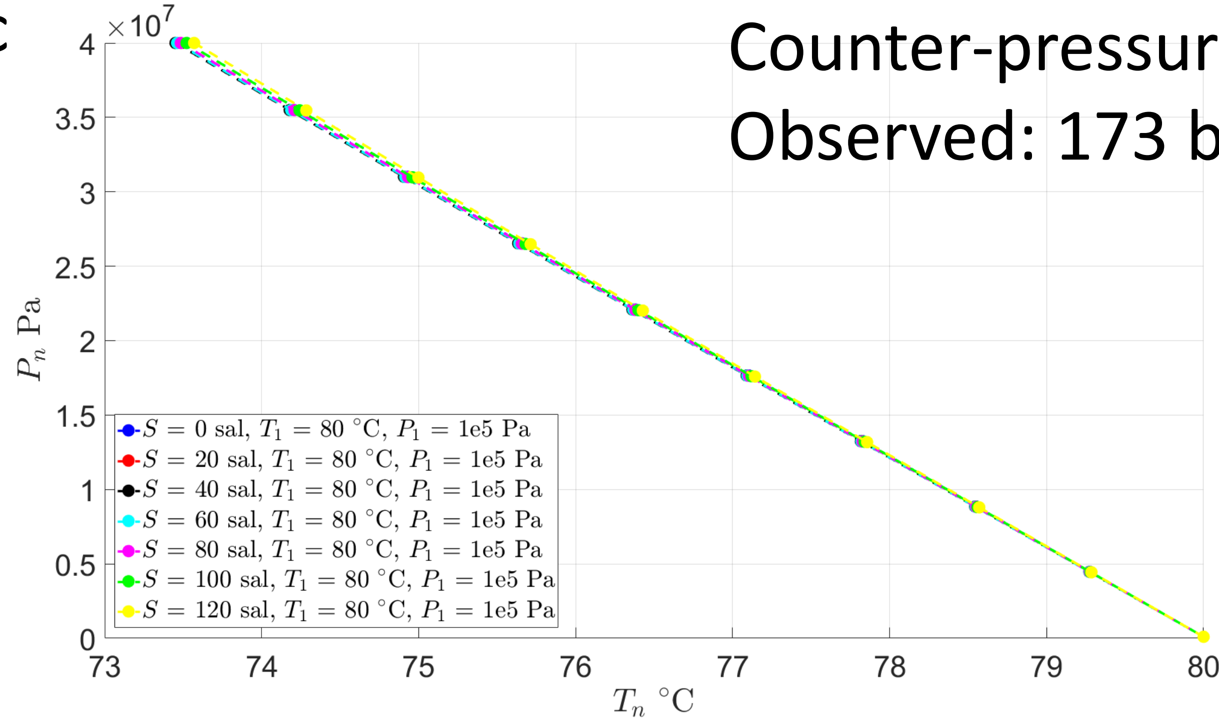
$$\Rightarrow \quad [\Delta p]_{J_w=0} = \frac{r_{\mathrm{wq}}^{\mathrm{tot}}}{r_{\mathrm{qq}}^{\mathrm{tot}}} \frac{\Delta T}{T V_w}$$

The pressure is rising on the cold solution side!

Soret equilibrium for solutions of the same salinity I

Thermo-osmotic pressure

Counter-pressure
Observed: 173 bar



Temperature on permeate side

Rententate side is 80 °C and 10^5 Pa.

Coefficients from l-g simulations, flat interfaces

Conclusions

- A theoretical description has been developed for the MemPower Concept. The model is checked for consistency

- Interface transfer coefficients need be further investigated to explain experimental results for pure water, salt solutions….

- The equations predict the theormo-osmotic pressure: a maximum limit for counter-pressure

- A promising concept for waste heat utilization?

Thank you for the attention!

Welcome to Trondheim!

PoreLab
NTNU-UiO Porous Media Laboratory

Norwegian Centre of Excellence
The Research Council of Norway

The overall coefficients - contributions

$$r_{\mathrm{qq}}^{\mathrm{tot}} = r_{\mathrm{qq}}^{I} + r_{\mathrm{qq}}^{II} + r_{\mathrm{qq}}^{III} + r_{\mathrm{qq}}^{IV} \tag{A.27}$$

$$\begin{aligned} r_{\mathrm{qw}}^{\mathrm{tot}} &= r_{\mathrm{qw}}^{I} + r_{\mathrm{qq}}^{I}\Delta_{15}H_{w,T} + r_{\mathrm{qw}}^{II} + r_{\mathrm{qq}}^{II}\Delta_{25}H_{w,T} \\ &+ r_{\mathrm{qw}}^{III} + r_{\mathrm{qq}}^{III}\Delta_{45}H_{w,T} + r_{\mathrm{qw}}^{IV} + r_{\mathrm{qq}}^{IV}\Delta_{55}H_{w,T} \end{aligned} \tag{A.28}$$

$$\begin{aligned} r_{\mathrm{wq}}^{\mathrm{tot}} &= r_{\mathrm{wq}}^{I} + r_{\mathrm{qq}}^{I}\Delta_{12}H_{w,T} + r_{\mathrm{wq}}^{II} + \left(r_{\mathrm{qq}}^{I} + r_{\mathrm{qq}}^{II}\right)\Delta_{23}H_{w,T} \\ &+ r_{\mathrm{wq}}^{III} + \left(r_{\mathrm{qq}}^{I} + r_{\mathrm{qq}}^{II}\right)\Delta_{34}H_{w,T} + r_{\mathrm{wq}}^{IV} + \left(r_{\mathrm{qq}}^{I} + r_{\mathrm{qq}}^{II} + r_{\mathrm{qq}}^{III}\right)\Delta_{45}H_{w,T} \\ &= r_{\mathrm{qw}}^{\mathrm{tot}} \end{aligned} \tag{A.29}$$

$$\begin{aligned} r_{\mathrm{ww}}^{\mathrm{tot}} &= r_{\mathrm{tot}}^{I} + r_{\mathrm{wq}}^{I}\Delta_{15}H_{w,T} + (r_{\mathrm{qw}}^{I} + r_{\mathrm{qq}}^{I}\Delta_{15}H_{w,T})\Delta_{12}H_{w,T} \\ &+ r_{\mathrm{ww}}^{II} + r_{\mathrm{wq}}^{II}\Delta_{25}H_{w,T} + (r_{\mathrm{qw}}^{I} + r_{\mathrm{qq}}^{I}\Delta_{15}H_{w,T} + r_{\mathrm{qw}}^{II} + r_{\mathrm{qq}}^{II}\Delta_{25}H_{w,T})\Delta_{23}H_{w,T} \\ &+ r_{\mathrm{ww}}^{III} + r_{\mathrm{wq}}^{III}\Delta_{45}H_{w,T} + (r_{\mathrm{qw}}^{I} + r_{\mathrm{qq}}^{I}\Delta_{15}H_{w,T} + r_{\mathrm{qw}}^{II} + r_{\mathrm{qq}}^{II}\Delta_{25}H_{w,T})\Delta_{34}H_{w,T} \\ &+ r_{\mathrm{ww}}^{IV} + r_{\mathrm{wq}}^{IV}\Delta_{55}H_{w,T} + (r_{\mathrm{qw}}^{I} + r_{\mathrm{qq}}^{I}\Delta_{15}H_{w,T} \\ &+ r_{\mathrm{qw}}^{II} + r_{\mathrm{qq}}^{II}\Delta_{25}H_{w,T} + r_{\mathrm{qw}}^{III} + r_{\mathrm{qq}}^{III}\Delta_{45}H_{w,T})\Delta_{45}H_{w,T} \end{aligned} \tag{A.30}$$