Engineering Conferences International
ECI Digital Archives

Advanced Membrane Technology VII | Proceedings

9-12-2016

Engineering of pervaporation systems: Modelling of dehydration modules, including recycles

Cilian O'Súilleabháin
Cork Institute of Technology, Ireland, cilian.osuilleabhain@cit.ie

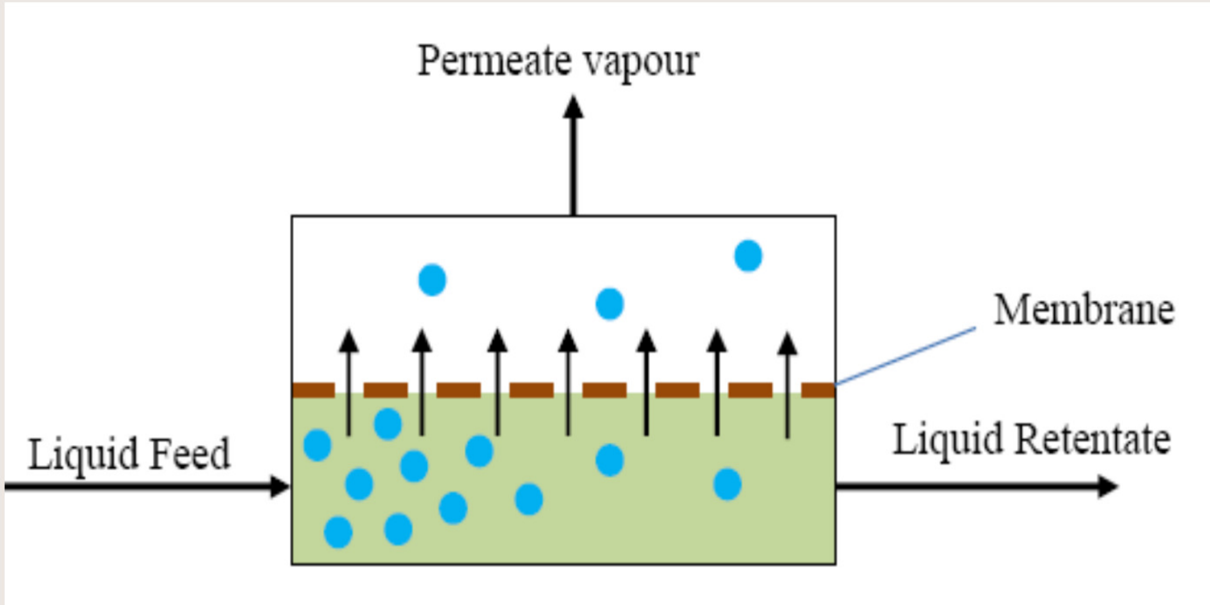
Greg Foley
Dublin City University, Ireland

Engineering of pervaporation systems: modelling of dehydration modules, including recycles

Cilian Ó Súilleabháin
Dr. Greg Foley

Dublin City University

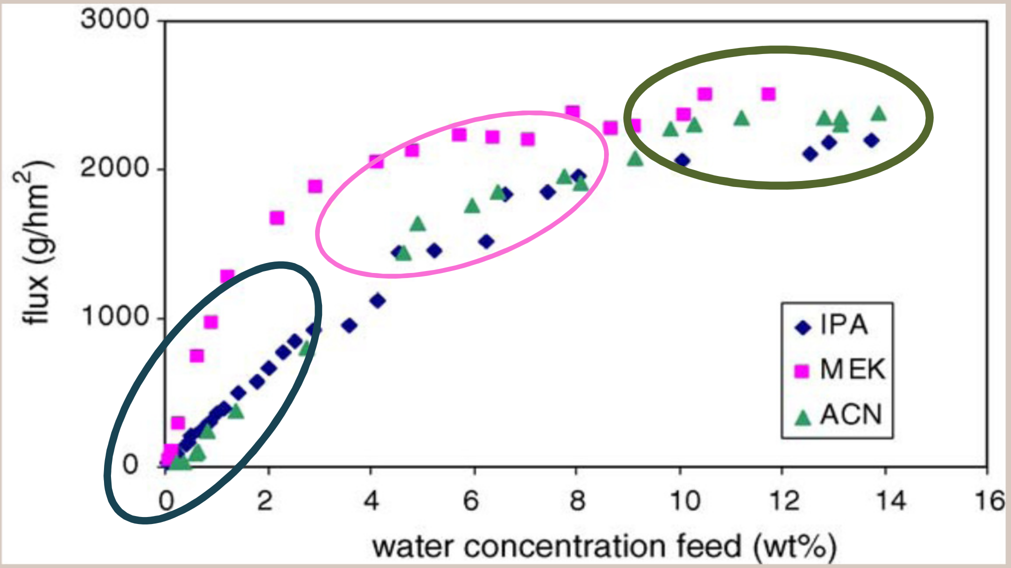
Pervaporation: adiabatic modules



Evaporation needs latent heat

- this causes the liquid to cool
- leading to reducing flux

Flux versus concentration: 3 scenarios



1. Flux proportional to % water (typical)
2. Transition zone
3. Flux is independent of concentration

Van Hoof,et al., (2006), Performance of Mitsui NaA type zeolite membranes for the dehydration of organic solvents in comparison with commercial polymeric pervaporation membranes, *Sep .Sci. Tech.,* 48 (2006) 304–309

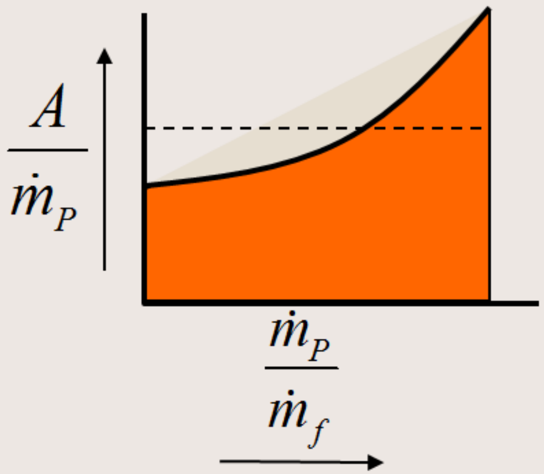
Flux is a function of temperature

$$J = J_o e^{\frac{-E_j}{RT}}$$

$$T = \frac{h_v}{c_p} - \left(\frac{h_v}{c_p} - T_f \right) \frac{\dot{m}_f}{\dot{m}}$$

Inverse flux

$$\frac{dA}{d\dot{m}} = -\frac{1}{J_o} e^{\frac{E_j}{R\left[\frac{h_v}{c_p} - \left(\frac{h_v}{c_p} - T_f\right)\frac{\dot{m}_f}{\dot{m}}\right]}}$$



Area below curve = $\frac{A}{\dot{m}_f}$

Integrating

$$\int_{1-\dot{m}_p/\dot{m}_f}^{1} e^{\frac{a}{b-(b-1)/s}}\,ds = \left.\frac{b\left(b\left(s-1\right)+1\right)e^{\frac{as}{b(s-1)+1}} - a\left(b-1\right)e^{a/b}Ei\left(\frac{a\left(b-1\right)}{b\left(b\left(s-1\right)+1\right)}\right)}{b^2}\right|_{1-\dot{m}_p/\dot{m}_f}^{1}$$

$$taking: \qquad p=\frac{\dot{m}_p}{\dot{m}_f} \qquad a=\frac{E_j}{RT_f} \qquad b=\frac{h_v}{c_pT_f}$$

$$\frac{J_{av}}{J_f}=\frac{b^2e^a p}{be^a - a\left(b-1\right)e^{a/b}Ei\left(\frac{a\left(b-1\right)}{b}\right) - b\left(1-bp\right)e^{\frac{a(1-p)}{1-bp}} + a\left(b-1\right)e^{a/b}Ei\left(\frac{a\left(b-1\right)}{b\left(1-bp\right)}\right)}$$

Envelope of Industrial Operations

Ethanol ≤ 15% water

IPA ≤ 20% water

Feed Temperature: 350 – 395K

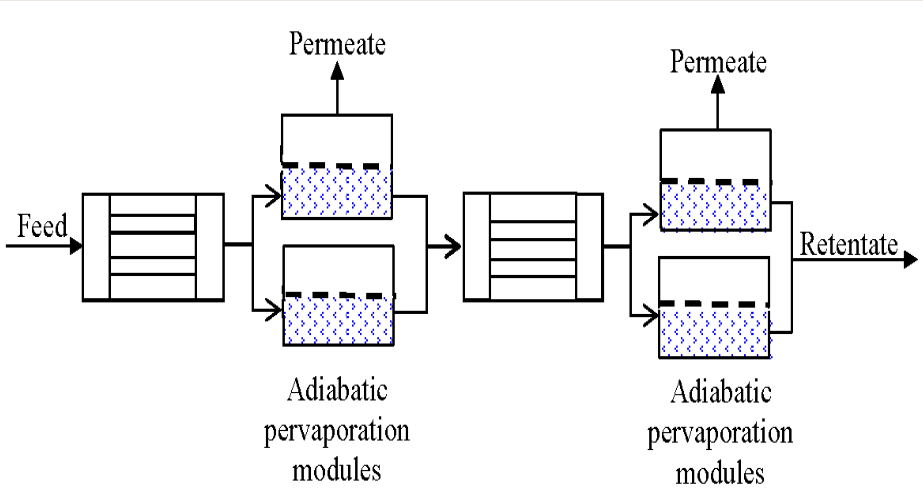
Permeate ≤ 5% of feed

$\Delta T \leq 30$ K

Baker, R.W., (2012), *Membrane Technology and Applications*, 3rd ed., John Wiley & Sons, Chichester, UK.

Permeate ≥ 90% and is constant

$$J = \frac{\dot{m}_p}{A} = J_o e^{\frac{-E_j}{RT}}$$



Calculation of maximum feasible E_J

Noted that: $J_r/J_f \geq 0.40$

Capital cost of reheating more economical than large membrane area at low flux

$$0.4 = \frac{J_o \exp\left(\frac{-E_J}{RT_r}\right)}{J_o \exp\left(\frac{-E_J}{RT_f}\right)}$$

Calculation of maximum feasible E_j

$$E_{j\,max} = \frac{R\ Ln(0.4)}{\left(\frac{1}{T_f} - \frac{1}{T_r}\right)}$$

$$T_r = \frac{0.5\frac{\dot{m}_p}{\dot{m}_f}c_{pv}T_f - \frac{\dot{m}_p}{\dot{m}_f}\lambda + \left(1 - \frac{\dot{m}_p}{\dot{m}_f}\right)c_{pr}T_f}{0.5\frac{\dot{m}_p}{\dot{m}_f}c_{pv} + \left(1 - \frac{\dot{m}_p}{\dot{m}_f}\right)c_{pr}}$$

Alternatively: $T_r = T_f - 30K$

Significance of findings

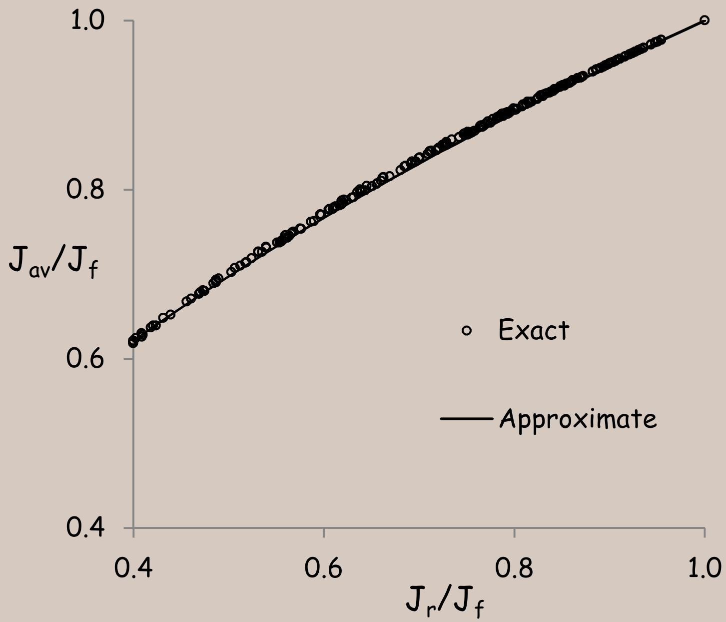
$E_{j\ max}$ is an additional metric for assessing membrane feasibility.

$E_{j\ max}$ completes envelope of industrial conditions.

Allows models to be tested for industrial conditions

C Ó Súilleabháin, G. Foley, Engineering of pervaporation systems: Exact and approximate expressions for the average flux during alcohol dehydration by single-pass pervaporation,, Sep. and Purif. Tech., 152 (2015) 160-163

Short cut equation



$$\frac{J_{av}}{J_f} = \left(\frac{J_r}{J_f}\right)^{0.52}$$

n = 0.52 error < 1.2% within industrial envelope

for all combinations of T_f, z_i, y_i, E_j, $\dot{m}_p/\dot{m}_f$

Sizing a pervaporation module

- Choose max T_f for membrane
- Choose $\dot{m}_p/\dot{m}_f$ ratio
- Use energy balance to calculate T_r
- Calculate J_f and J_r
- Calculate J_{av}/J_f
- Calculate Area

$$A = \frac{\dot{m}_f \left(\dfrac{\dot{m}_p}{\dot{m}_f} \right)}{J_f \left(\dfrac{J_{av}}{J_f} \right)}$$

Significance of Findings

Membrane area can be calculated easily.

No longer dependent on suppliers for data

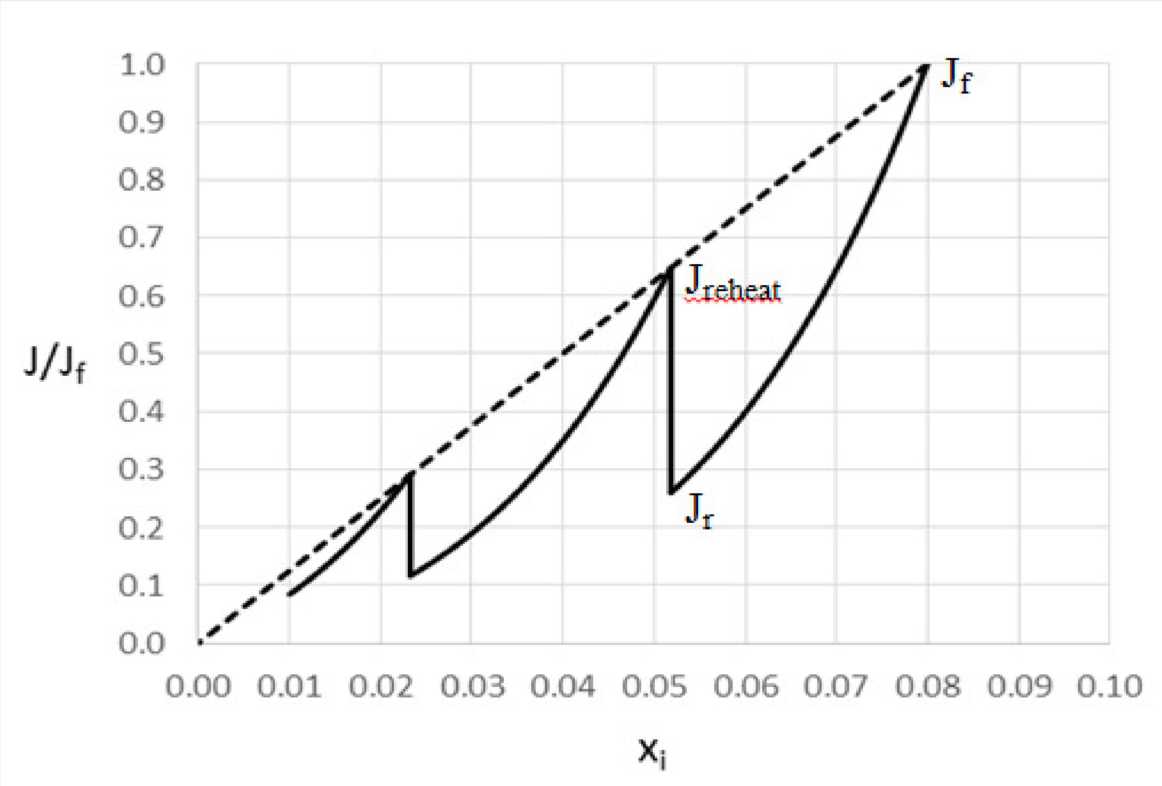
Should encourage adoption of pervaporation

Only applicable where flux independent of conc.

Ideal systems – need "efficiency factor"

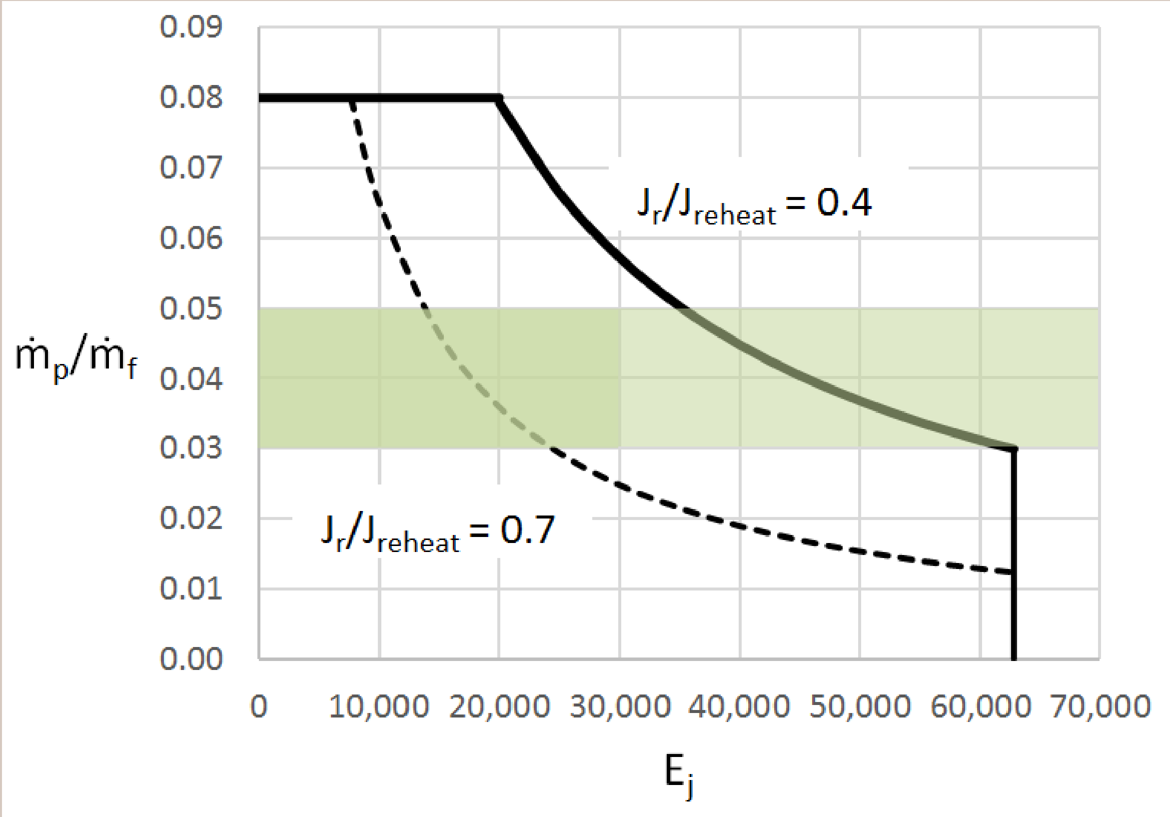
C Ó Súilleabháin, G. Foley, Engineering of pervaporation systems: Exact and approximate expressions for the average flux during alcohol dehydration by single-pass pervaporation,, Sep. and Purif. Tech., 152 (2015) 160-163

J_r/J_{reheat} ratio



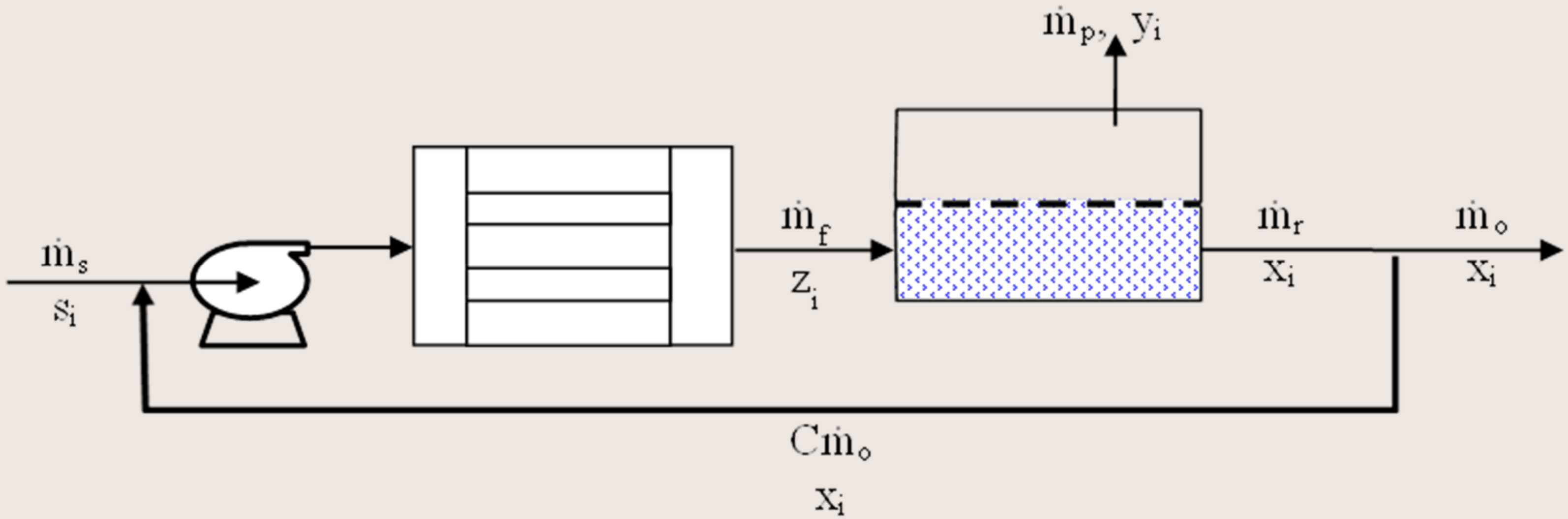
IPA-water, T_f = 120 °C, E_j = 15,000 & 45,000 kJ/kmol

$\dot{m}_p/\dot{m}_f$ ratios



IPA-water, $T_f = 120^oC$, $y_i = 0.90$, feed 16% water

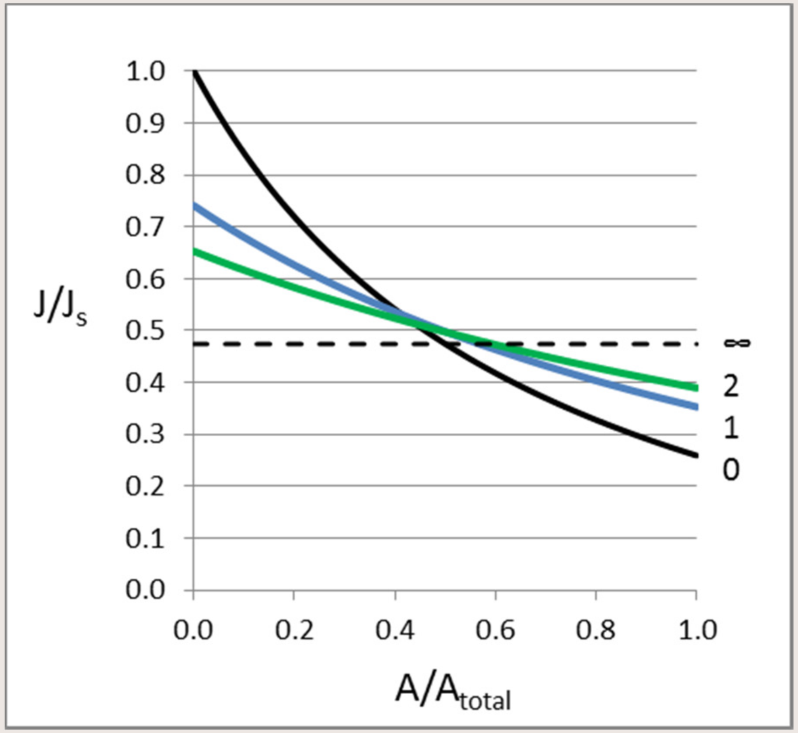
Recycles



Increased liquid flow through module reduces ΔT thus increasing average flux

- but reduced conc. may counteract this

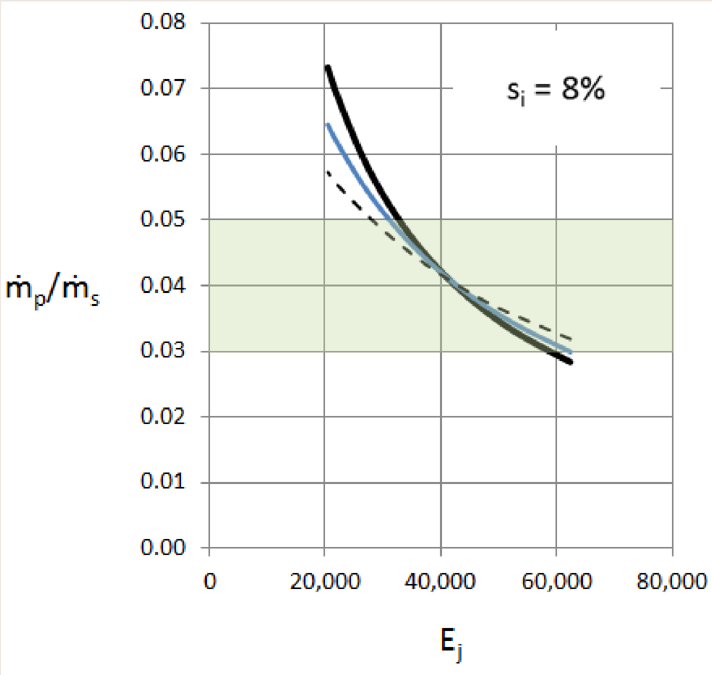
Effect of concentration and temp

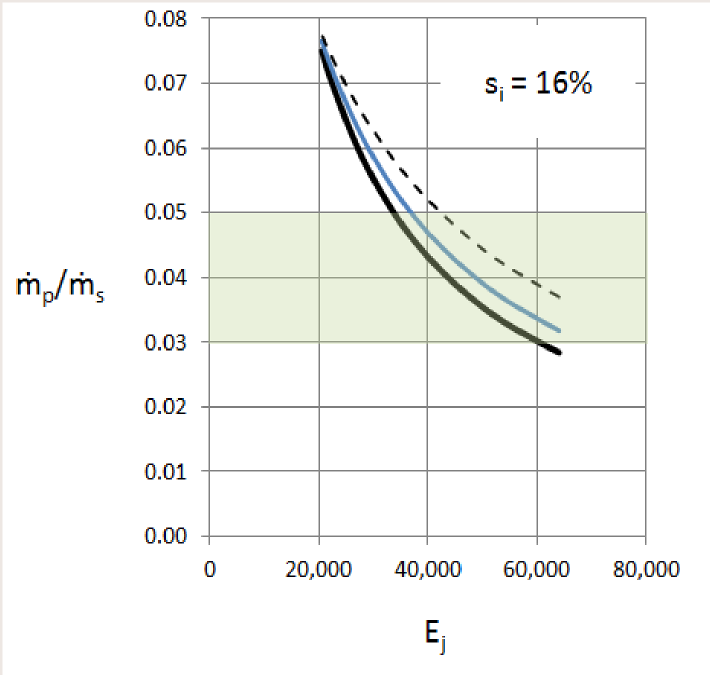


Lower feed conc. reduces flux at inlet
Higher temp increases flux at outlet

IPA, s_i = 5%, Ej = 40,000 kJ/kmol, T_f = 120^oC, y_i = 0.9

Recycle results - IPA





s_i = 8%

s_i = 16%

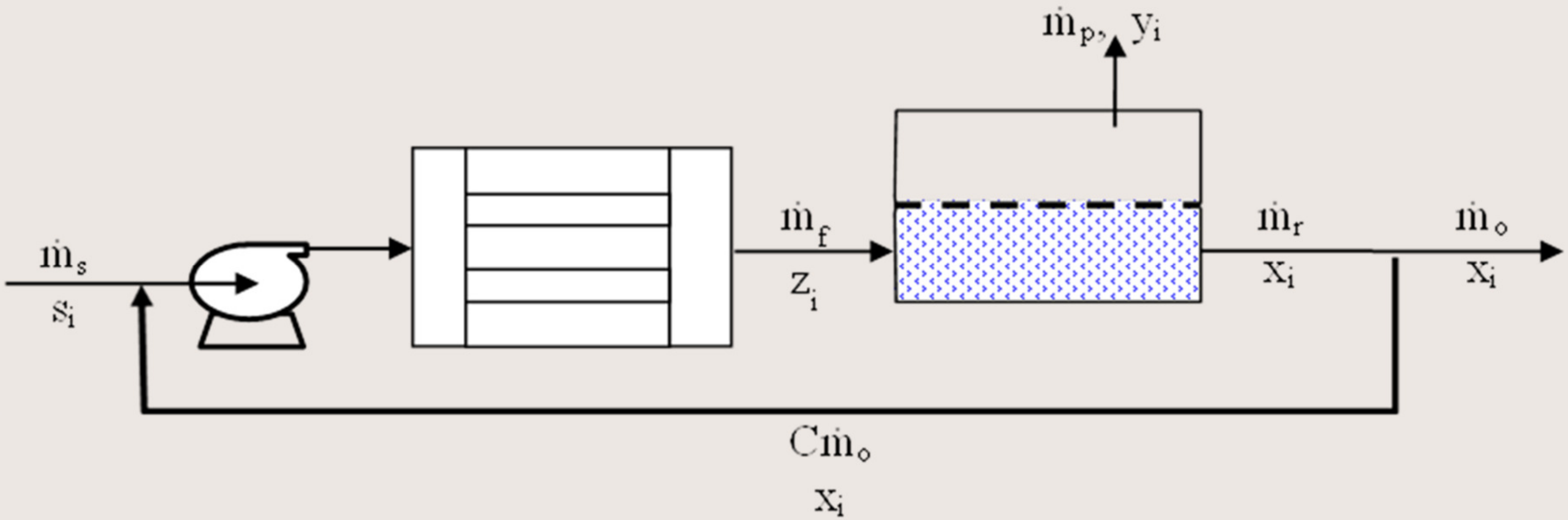
$C = 0$, $C = 1$ and $C = \infty$

Recycle: mass balance equations

$$\frac{\dot{m}_p}{\dot{m}_r} = \frac{\dfrac{\dot{m}_p}{\dot{m}_s}}{\left[(1+C)\left(1-\dfrac{\dot{m}_p}{\dot{m}_s}\right)\right]}$$

$$z_i = \frac{s_i + C\left(s_i - \dfrac{\dot{m}_p}{\dot{m}_s} y_i\right)}{1 + C\left(1-\dfrac{\dot{m}_p}{\dot{m}_s}\right)}$$

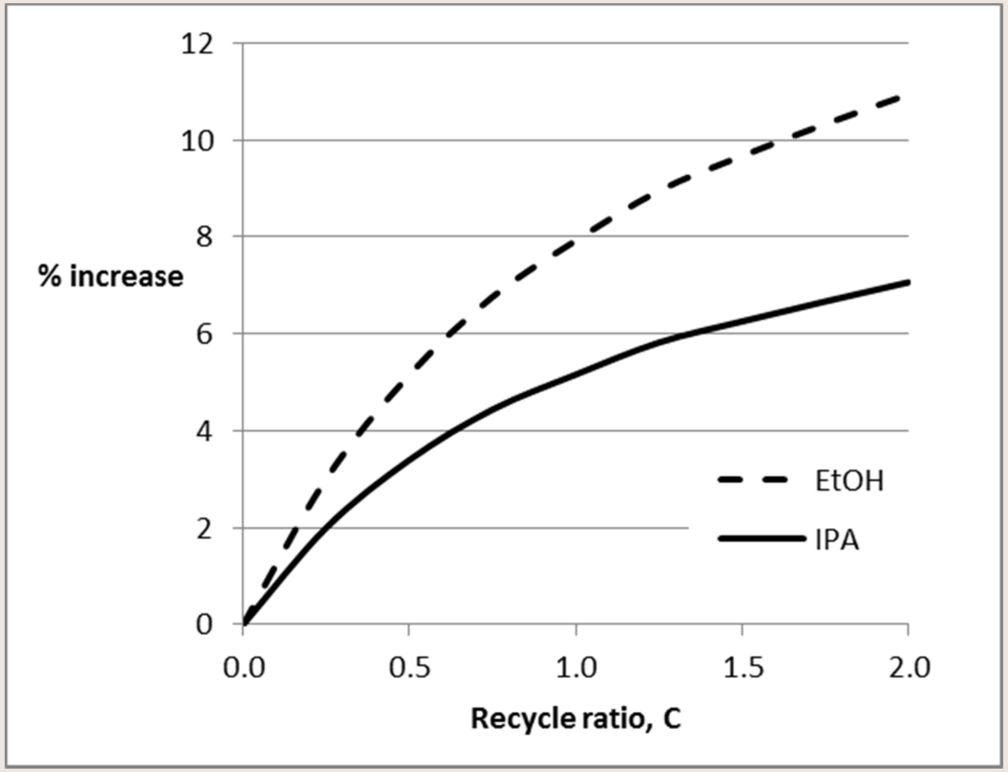
Increasing throughput – x_i unchanged



Increase $\dot{m}_p$ and $\dot{m}_s$ equally

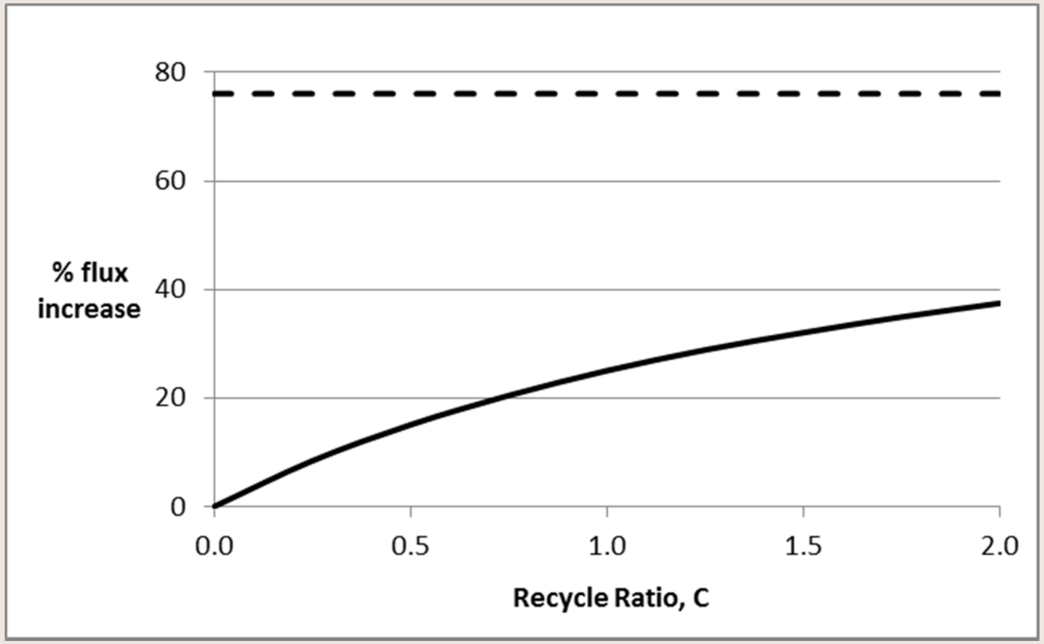
=> x_i is unchanged

Increasing throughput – x_i unchanged



Increase in throughput vs. recycle ratio for isopropanol dehydration with flux proportional to concentration, s_i= 10 wt%, T_f = 120°C, y_i = 95% water, E_j = 40,000 kJ/kmol, $\dot{m}_p/\dot{m}_s$ = 0.03
Dashed line shows ethanol.

Desalination



Brine $s_i = 3.49\%$, $T_f = 70\ ^oC$, $\dot{m}_p/\dot{m}_s = 0.03$ and $E_J = 54{,}000$ kJ/kmol.

Data from: Peng, P., Fane, A.G., Xiaodong, L., Desalination by membrane distillation adopting a hydrophilic membrane, Desalination, 173 (2005) 45-54.

Recycle

- Can lead to increased flux
- Best at high E_j and high z_i (Santoso et al.)

- Better if flux independent of conc.
- Equations for conc. and flow ratios
- Purer retentate or greater throughput
- Flexibility for industry

Santoso, A., Cheng-Ching, Y., Ward, J.D., Analysis of local recycle for membrane pervaporation systems, Ind. Eng. Chem. Res., 2012, 51, 9790-9802

Go raibh maith agaibh

Questions?