Membrane processes

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Lecture 13

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Reference book: Membrane Technology and Applications, R. W. Baker, Wiley 2012 (3rd ed.)

Question 1

https://forms.gle/nM12JhxifkmdQh4D9

A single membrane stage for CO_2/N_2 separation achieves CO_2 recovery of 30% and CO_2 purity of 60%. What do we expect if we add a second stage fed with the permeate of the single stage?

a. Higher CO_2 recovery, lower CO_2 purity
b. Lower CO_2 recovery, higher CO_2 purity
c. Same CO_2 recovery, higher CO_2 purity
d. Same CO_2 purity, higher CO_2 recovery

Question 2

The CO_2 recovery from a single stage decreases when selectivity increases (with fixed CO_2 permeance) because of:

a. The reduction in N_2 permeance
b. The decrease of driving force for CO_2 flux
c. The increase in purity
d. All the above are correct.

Question 3

The CO_2 purity from a single stage decreases when feed pressure increases because:

a. The flux of CO_2 increases
b. The flux of N_2 increases
c. The CO_2 permeance is lower
d. The N_2 permeance is higher

Question 4

In a double stage, the total CO_2 recovery reaches a maximum and then it decreases when we increase the feed pressure of the first stage because:

a. Beyond that pressure, membranes start to break
b. The recovery is limited by the permeate flow of the second stage
c. The driving force for the flux in the first stage first increases then decreases
d. Purity achieves a plateau

Question 5

Non-ideal phenomena:

a. Damage the membranes
b. Reduce the available driving force
c. Do not allow to achieve high recovery
d. Cause the presence of impurities in the permeate

Question 6

Pressure drops can be minimized by:

a. Increasing feed velocity
b. Reducing feed velocity
c. Reducing channel thickness
d. Increasing membrane selectivity

Question 7

The effect of concentration polarization is stronger at:

a. Higher channel thickness
b. Higher feed velocity
c. Lower membrane permeance
d. Higher membrane selectivity

Question 8

If membranes have higher permeance, the concentration polarization effect:

a. Increases because the flux from the bulk to the interface reduces
b. Increases because the trans-membrane flux increases
c. Decreases because the mass transfer coefficient is higher
d. Does not change

In-class exercise

Exercise: Concentration polarization and Pressure drops

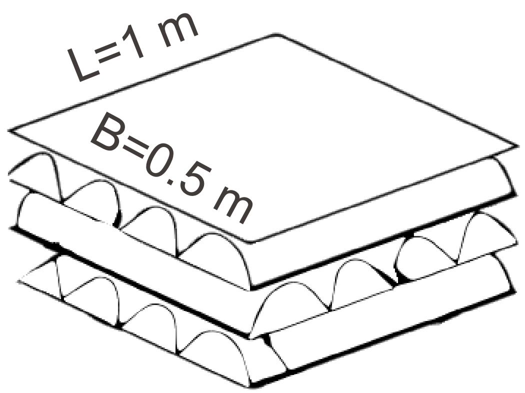
- A gas permeation module with cross-current flow arrangement is separating CO2 from N2 using a membrane with a CO2/N2 selectivity of 16.9 and CO2 permeability of 3.3 x 10-14 mole m-1 s-1 Pa-1. Feed to the membrane contains 20 mol% CO2. Feed and retentate pressure are 5.5 bar and a permeate pressure is 1 bar. Membrane thickness is 1.0 µm.
- Membrane area is 60 m^2 and Q_{feed} is 1 mol/s. The channel thickness is 100 µm. The dimensions of the membrane sheets are 0.5 m (width) x 1 m (length). Assume Re = 2000, density = 1.3 kg/m^3, k = 0.5 mol/m^2s
- Calculate the outlet purity and recovery.

$$N_{CO2} = 3.3 \times 10^{-8} \, {mol}/{m^2 s Pa} = 98.5 \, GPU$$

Ideal case with length discretization:

- Purity = 0.59
- Recovery = 0.35

- Only pressure drops



$$\frac{dP_{feed}}{dx} = -f\,\frac{\rho}{2\,d_{hydr}}v^2$$

$$d_{hydro} = \frac{4A}{P} = \frac{4\,B\times\delta}{2(B+\delta)} = 0.0002\,m$$

$$v = \frac{Q_f[mol/s]\,RT}{P}\left[{}^{m^3}/_{s}\right] \times \frac{1}{B\times\delta\times N_{channels}} = \frac{1\times 8.31\times 298}{5.5\times 10^5}\times\frac{1}{0.5\times 0.0001\times 120} = 0.75\,m/s$$

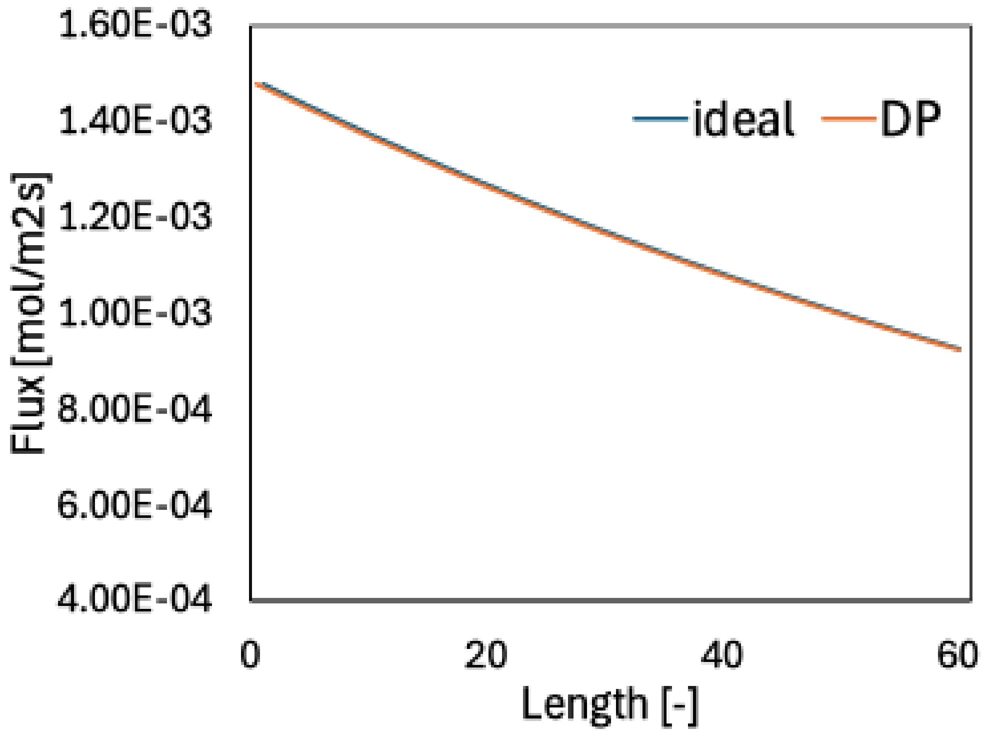
$$\frac{dP}{dx} = -\frac{f\rho}{2\,d_{hydr}}v^2 = -\frac{64}{2000}\times\frac{1.3}{2\,\times\,0.0002}\times 0.75^2 = -58.6\frac{Pa}{m} = -0.00059\,bar/m$$

The profiles of $X_{CO2,perm}$ and J_{CO2} have to be recalculated considering the P decrease.

$$X_{CO2,perm}(x) = \frac{1+(\alpha-1)\left(\beta+X_{CO2,feed}(x)\right)-\sqrt{\left[1+(\alpha-1)\left(\beta+X_{CO2,feed}(x)\right)\right]^2-4\alpha\beta(\alpha-1)\,X_{CO2,feed}(x)}}{2\beta(\alpha-1)}$$

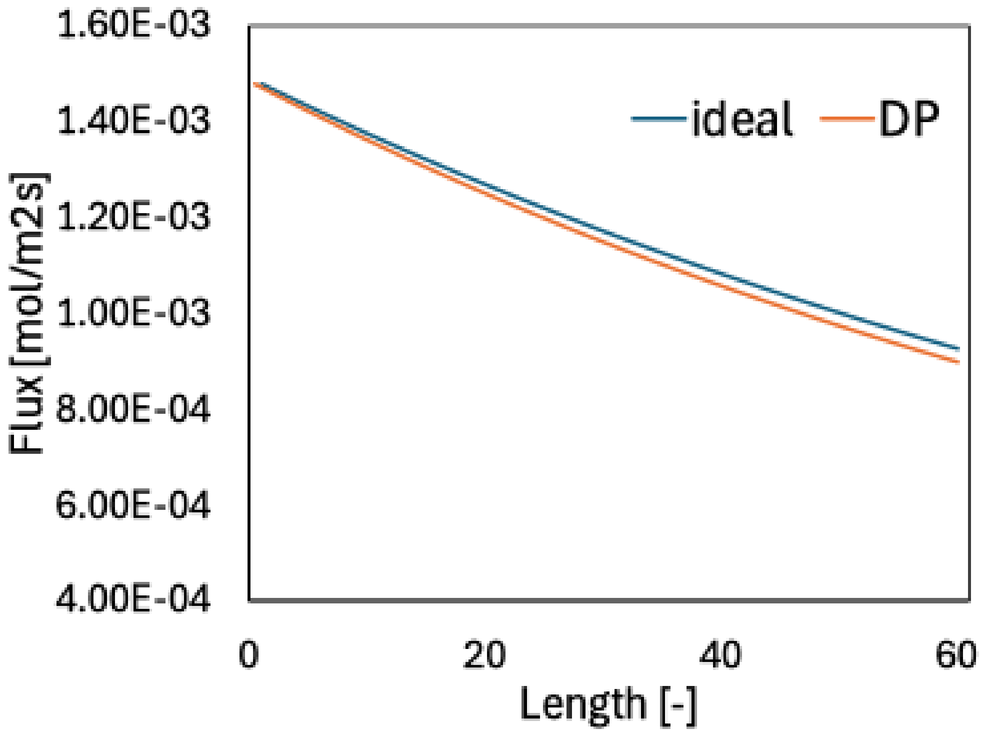
$$J_{CO2}(x) = \boldsymbol{N}_{CO2}\left(P_{feed}\,X_{CO2,feed}(x) - P_{perm}\,X_{CO2,perm}(x)\right)$$

- v = 0.75 m/s



Purity = 0.59
Recovery = 0.35

- v = 10 m/s



Purity = 0.59
Recovery = 0.348

- Only concentration polarization

$$\frac{X_1^p - X_1^{f,m}}{X_1^p - X_1^{f,b}} = exp\left(\frac{J_1 + J_2}{k}\right)$$

We would need an iterative loop where fluxes and X_{perm} are recalculated in function of $X^{f,m}$

Conservative assumption: CP index depends on the ideal flux at the entrance

$$\frac{X_1^p - X_1^{f,m}}{X_1^p - X_1^{f,b}} = exp\left(\frac{J_1 + J_2}{k}\right) = exp\left(\frac{J_{CO2}[0] + J_{N2}[0]}{k}\right)$$

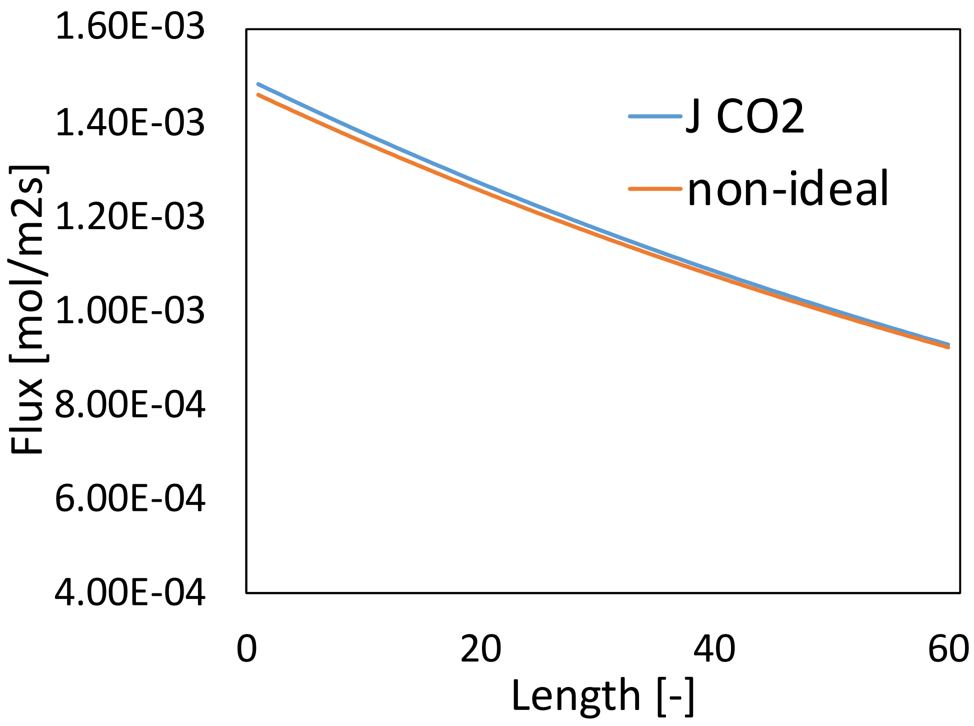
$$= \exp\left(\frac{0.00227}{0.5}\right) = 1.0045$$

For each element, we recalculate the $X_1^{f,m}$ from $X_1^{f,b}$ and X_1^p calculated as function of $X_1^{f,b}$ -> we recalculate X_1^p and use this for fluxes and balances

A	dA	Qf	Xf,b	Xp (id)	Xf,m	Xp (real)	J CO2	J N2	J tot	Qr	Xr
0.5	0.5	1	0.2	Calc from Xf,b = 0.65	Calc from exp(J/k)	Calc from Xf,m	Calc from Xp,real	Calc from Xp,real	J CO2 + J N2	Calc from balance with J	Calc from balance with JCO2
1.5	0.5	Qr	Xr	Calc from Xf,b	Calc from exp(J/k)	Calc from Xf,m	Calc from Xp,real	Calc from Xp,real	J CO2 + J N2	Calc from balance with J	Calc from balance with JCO2

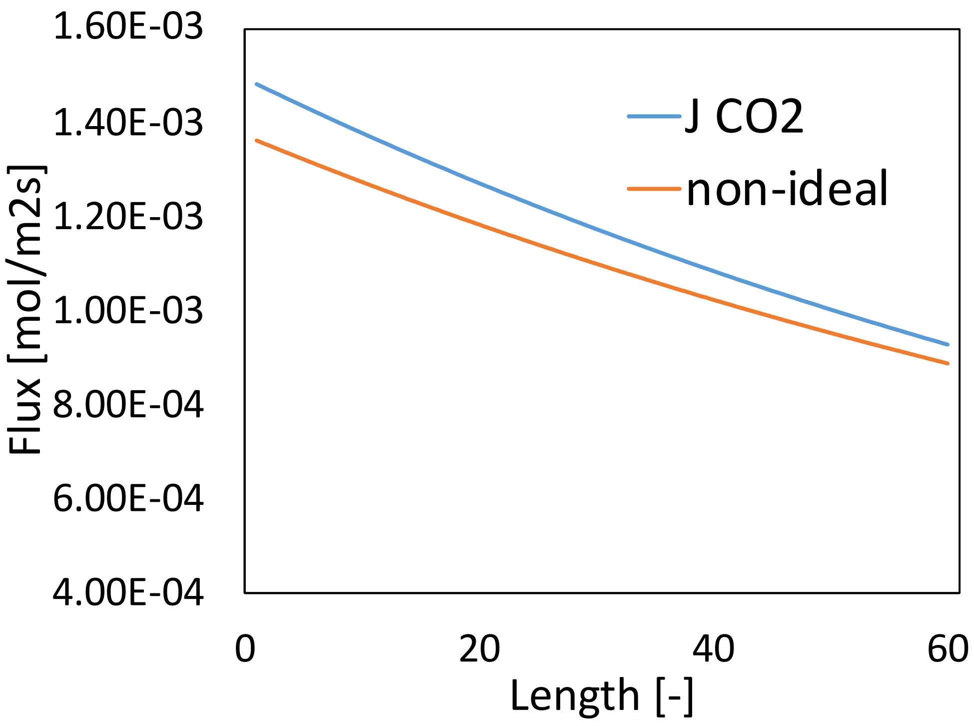
This is an approximation valid for limited concentration polarization

- k = 0.5 mol/m2s



Purity = 0.59
Recovery = 0.349

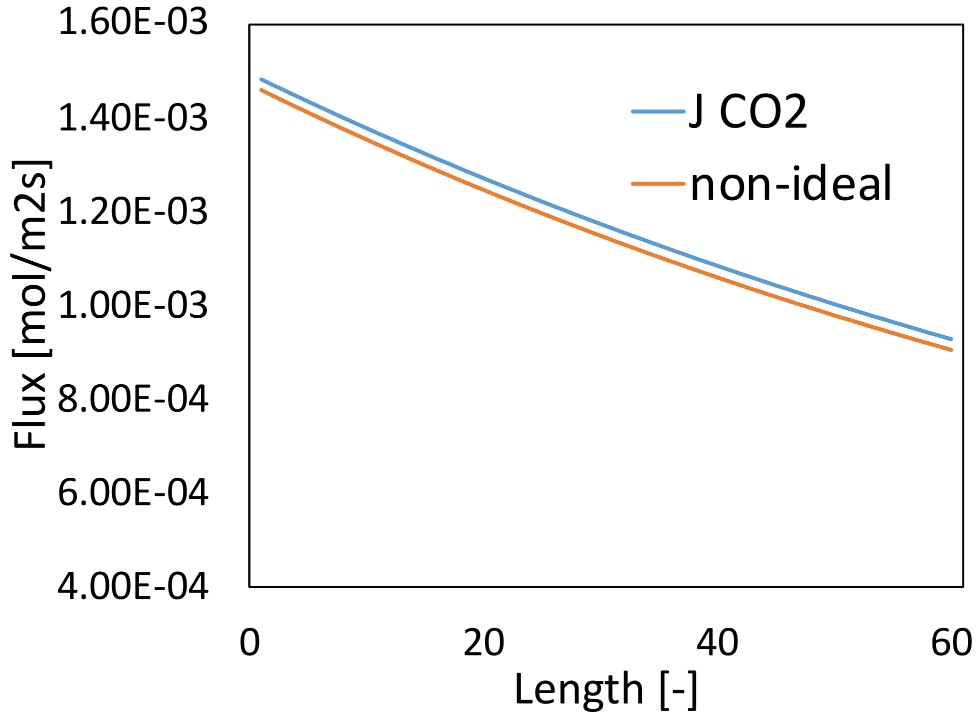
- k = 0.1 mol/m2s



Purity = 0.58
Recovery = 0.33

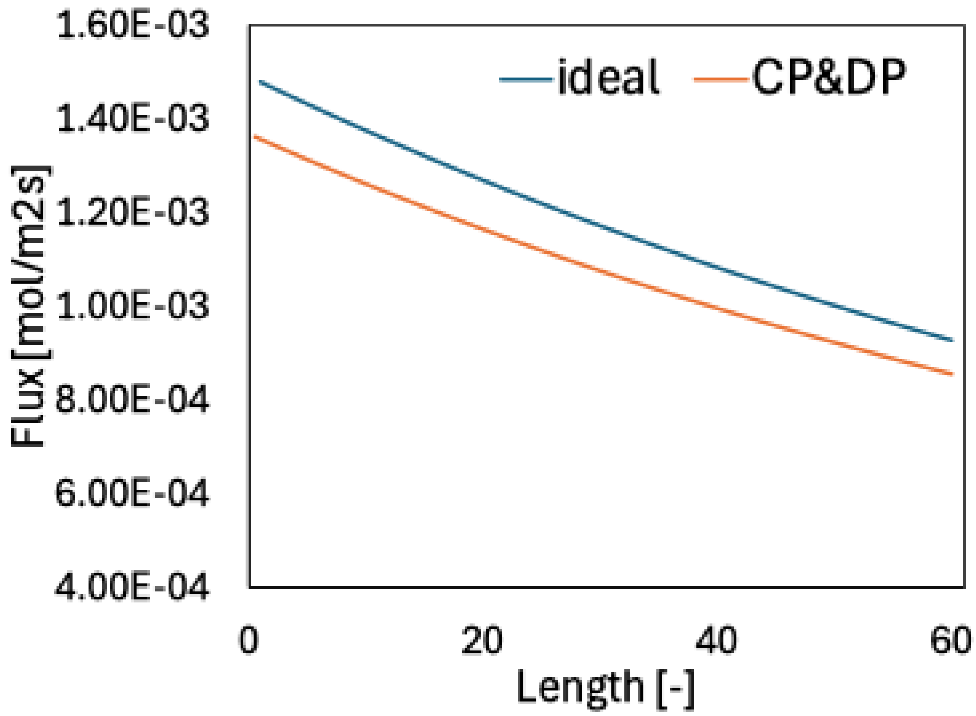
- Concentration polarization and pressure drops

- k = 0.5 mol/m2s
- v = 0.75 m/s



Purity = 0.59
Recovery = 0.349

- k = 0.1 mol/m2s
- v = 10 m/s

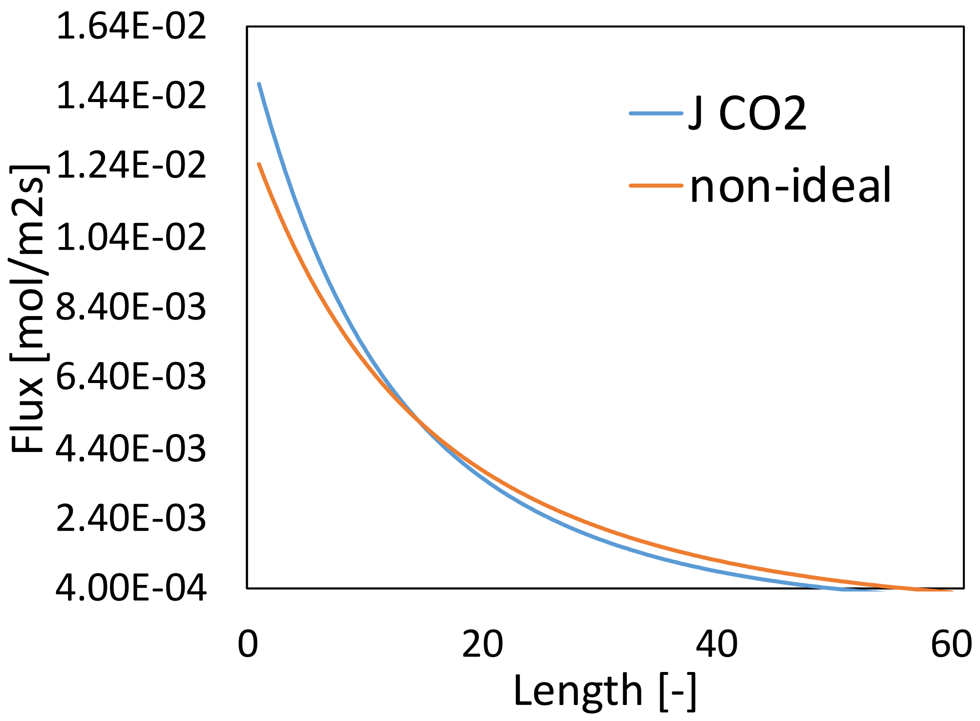


Purity = 0.575
Recovery = 0.326

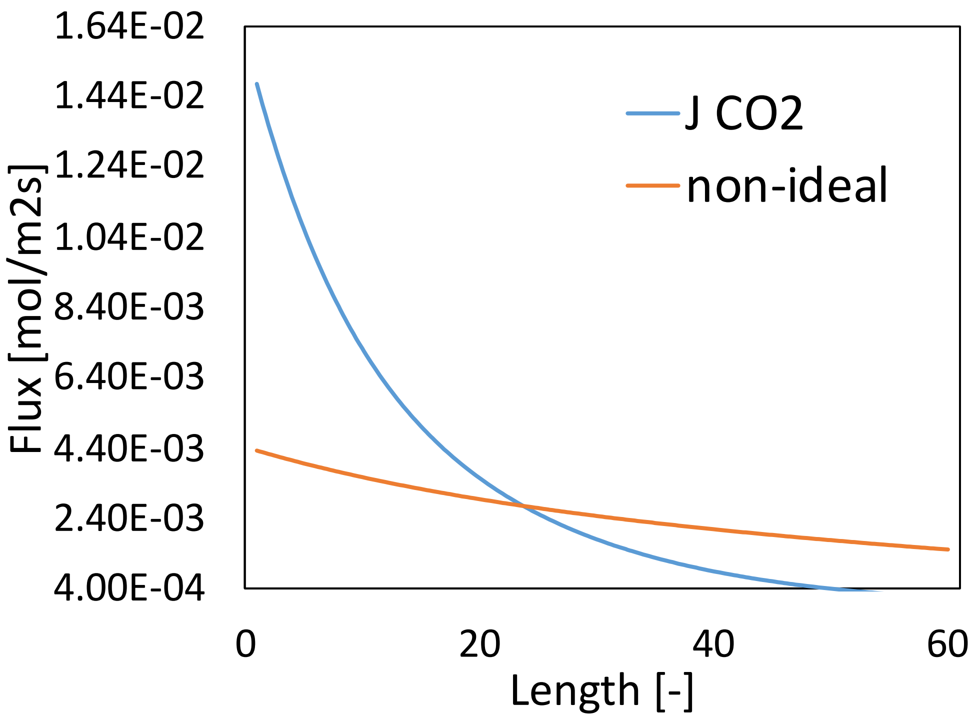
- Concentration polarization and pressure drops with higher permeance

$$N_{CO2} = 3.3 \times 10^{-7}\, {}^{mol}/_{m^2 sPa} = 985\ GPU$$

- k = 0.5 mol/m2s
- v = 0.75 m/s



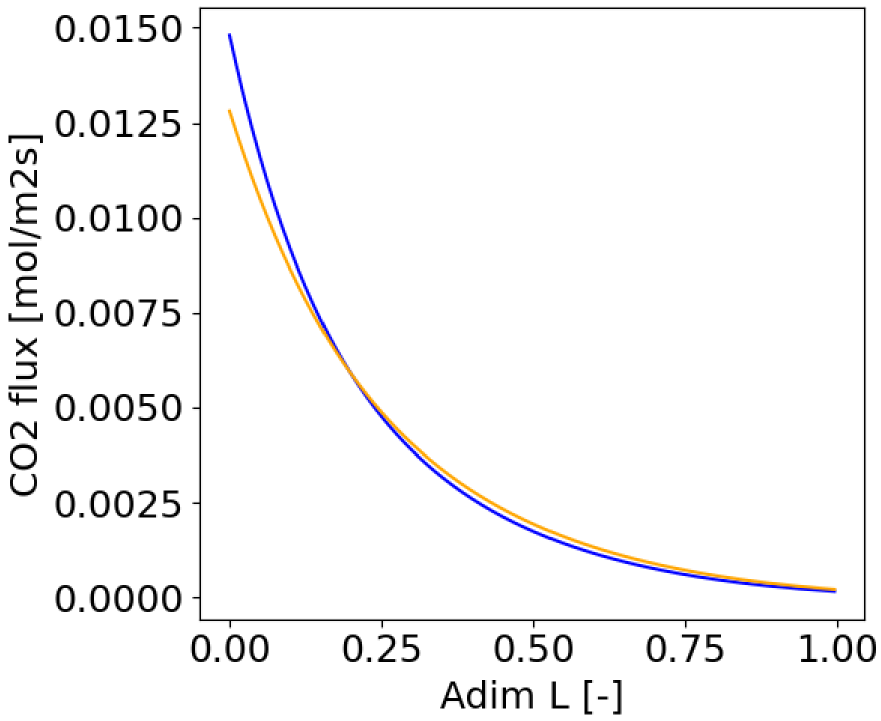
- k = 0.1 mol/m2s
- v = 2 m/s



Speaker

- Profiles from the rigorous model

- k = 0.5 mol/m2s



- k = 0.1 mol/m2s