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Filtration of several uncharged solutes on reverse osmosis membrane: Theory modification based on slip boundary

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Introduction

- Nanofiltration is a promising membrane technique with a large number of applications in treatment of process water, drinking water and wastewater.
- More specifically, nanofiltration can be used to remove small organic molecules. Models for nanofiltration are usually based on non-slip condition which can be modified to slip condition as a rational assumption.
- In this paper, the effects of slip length on the rejection of uncharged solutes such as glycerol and glucose along the effective membrane thickness have been investigated. The Bowen nanofiltration transport model based on Hagen–Poiseuille equation for solvent velocity (no slip condition) has been modified by several slip conditions and a new model allowing calculation of uncharged solute rejection on the basis of a binary membrane parameter (slip length and pore radius) was developed.

Model development

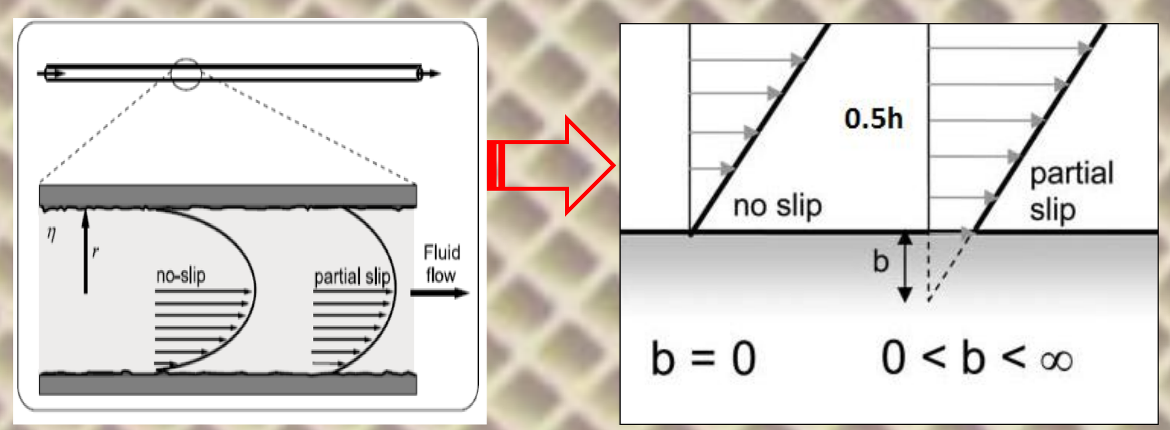


Fig. 1. Liquid slip in nanopore

1. The fundamental transport equation to be used for uncharged solutes

$$\begin{cases} J_s = K_c c u - \frac{c D_p}{RT}\frac{d\mu}{dx} \ (1) \\ \mu = RT \ln a + V_s P + Constant \ (2) \end{cases}$$

$$\rightarrow J_s = K_c c u - D_p \frac{dc}{dx} - \frac{c D_p}{RT} V_s \frac{dP}{dx} \ (3) \ \& \ J_s = c_p u \ (4)$$

2. The average velocity equation in a rectangular nanopore with considering slip length (b)

$$u = \frac{h^2}{12\eta}\left(1 + \frac{6b}{h}\right)\left(\frac{-dP}{dx}\right) \ (5)$$

$$\rightarrow \left(\frac{-dP}{dx}\right) = \frac{12\eta}{h^2 + 6bh} u \ (6)$$

3. Develop the Rejection Equation

$$(3),(4),(6) \rightarrow c_p = K_c c u - D_p \frac{dc}{dx} + \frac{c D_p}{RT} V_s \frac{12\eta}{h^2 + 6bh} u \ (7)$$

$$If \ \alpha = \frac{D_p}{RT} V_s \frac{12\eta}{h^2 + 6bh} \quad \& \quad \beta = K_c + \alpha$$

$$\text{and} \quad \epsilon = \frac{\left(1 - \frac{1}{\beta\emptyset}\right)}{\exp\left(\frac{u\beta z}{D_p}\right)} + \frac{1}{\beta\emptyset}$$

$$\Rightarrow \quad \boldsymbol{Rej = 1 - \frac{1}{\epsilon}}$$

Model procedure

Input Parameters
- Temperature
- Trans membrane pressure
- Pore size and Shape
- Ionic or uncharged solute radius
- Bulk feed concentration
- Bulk solvent viscosity
- Porosity
- Tortuosity
- Membrane thickness

Model Parameters calculation
- Fluid Slip Length
- Solvent viscosity in pore
- Uncharged solute/ ion concentration within pore entrance
- Velocity
- Effective pressure driving force
- Uncharged solute/ ion steric partition coeffiient
- Uncharged solute pore/ ion diffusion coefficient
- Uncharged solute/ ion hindrance factor for convection
- Solvent permeability
- Osmotic reflection coefficient.

Output Result
- Concentration of solute/ ion i within pore
- Concentration of solute/ ion i in concentration polarization layer
- Bulk permeate concentration
- Rejection
- Membrane material properties
- Model validation and errors
- etc.

Model Input

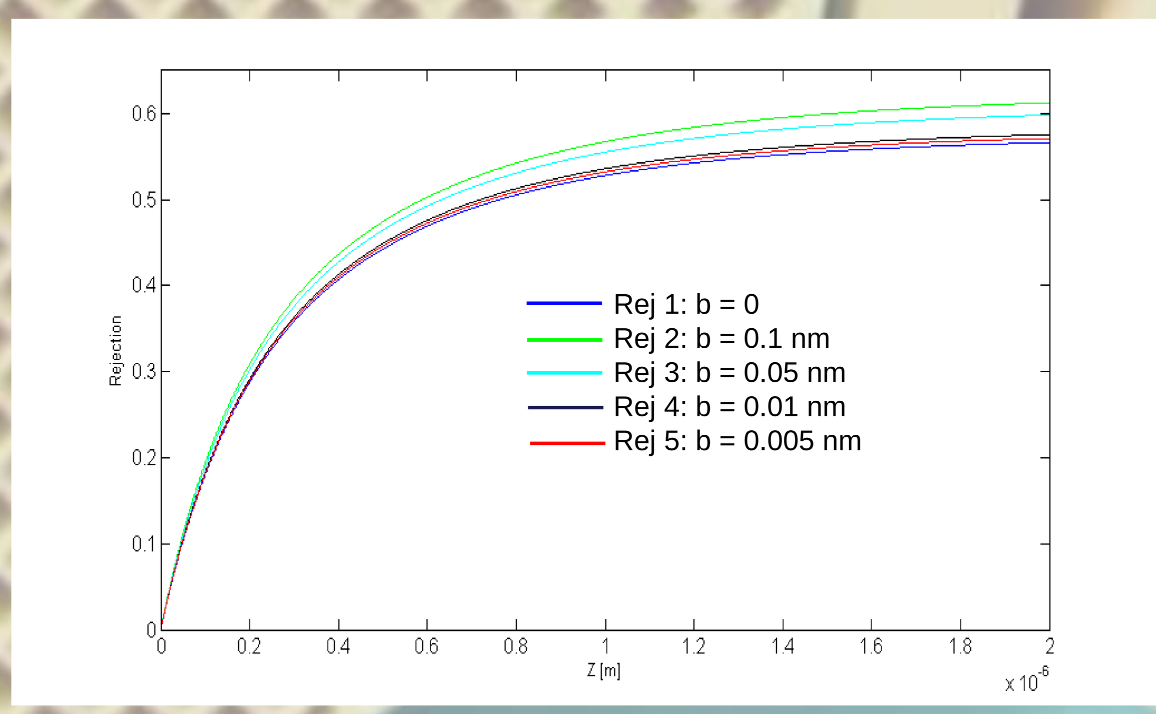
Parameter	Value	Description
u	1 [m h^{-1}]	solvent velocity
H	1[nm]	Pore height
b*	0.1-0.005 [nm]	Slip length
C_f	10 [mol m^{-3}]	bulk feed concentration
T	298.15 [K]	absolute temperature
η	0.001 [N s m^{-2}]	solvent viscosity within pores
Z	2 [µm]	Width of pore
N_p	10000000	The points number in pore

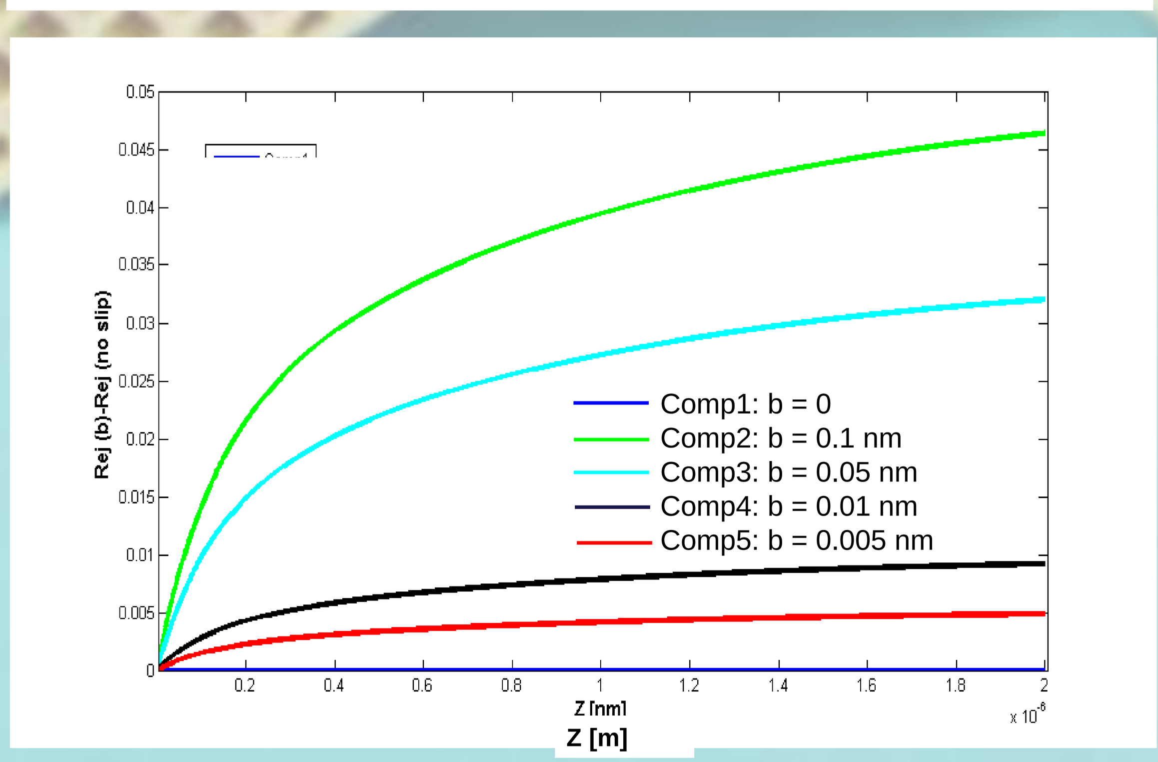
Solute	D_∞ ($10^{-9}m^2s^{-1}$)	r_s (nm)	V_s (cm^3mol^{-1})	Ref
Glycerol	0.95	0.26	70.8	Kiyosawa (1991)
Glucose	0.69	0.365	110	Birch (1997)

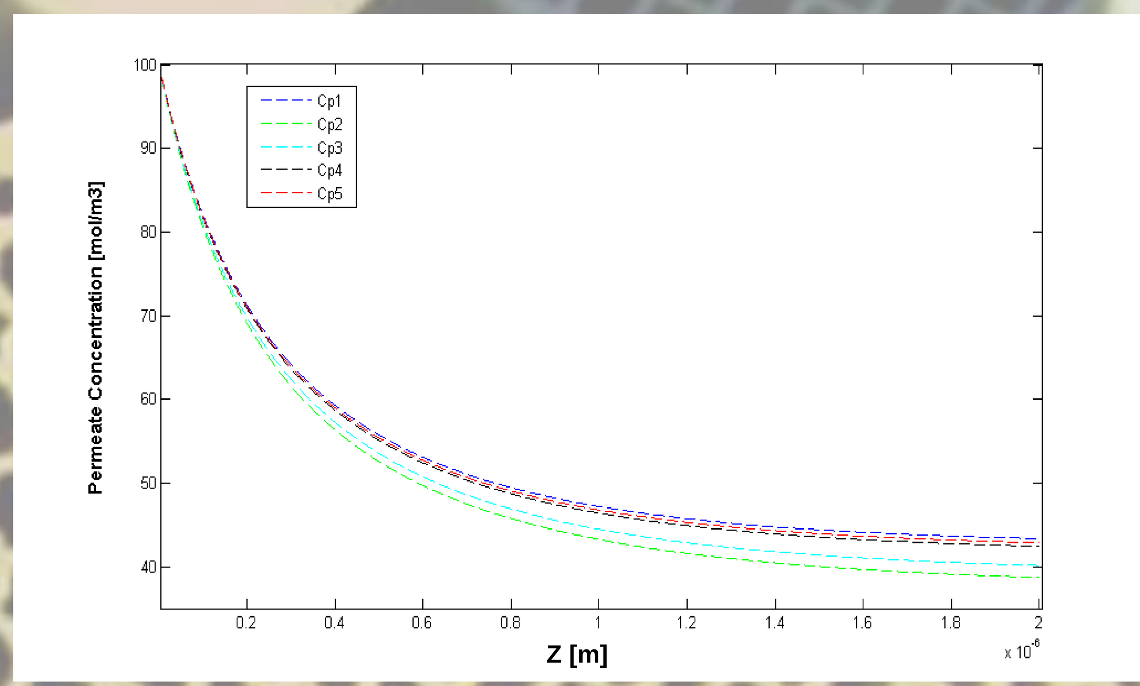
Results

1. Glycerol

Rej/ΔRej/ Conc. vs. Pore Length Z for various slip lengths b ((1-5): b= [0, 1e-10, 5e-11, 1e-11, 5e-12] m

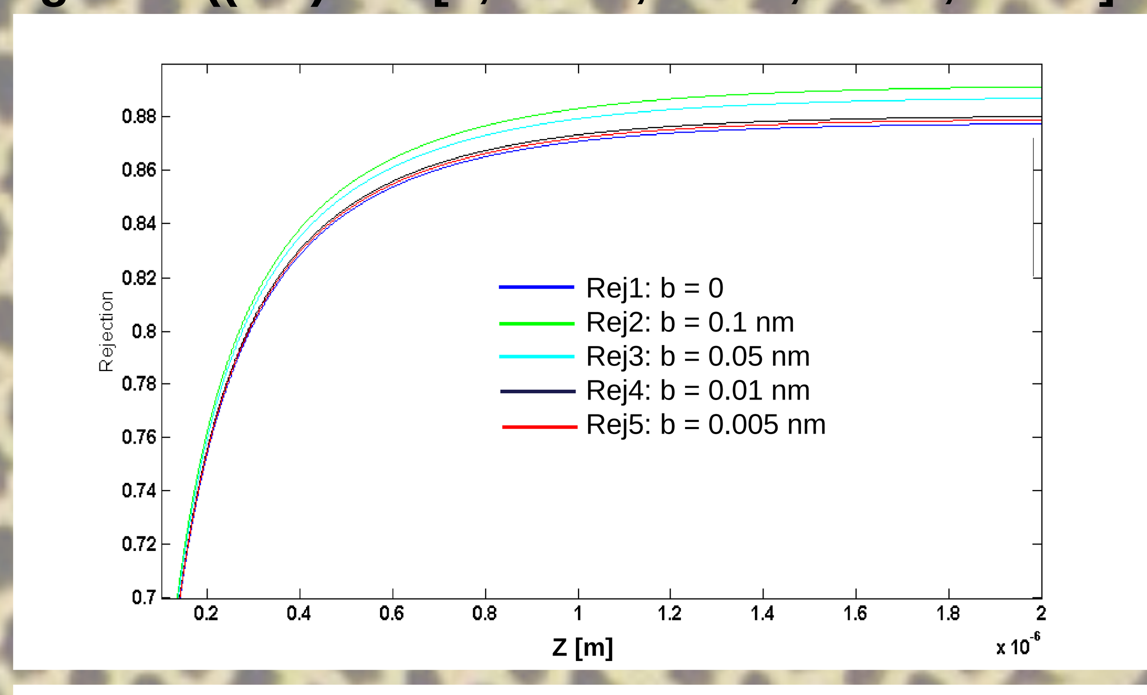


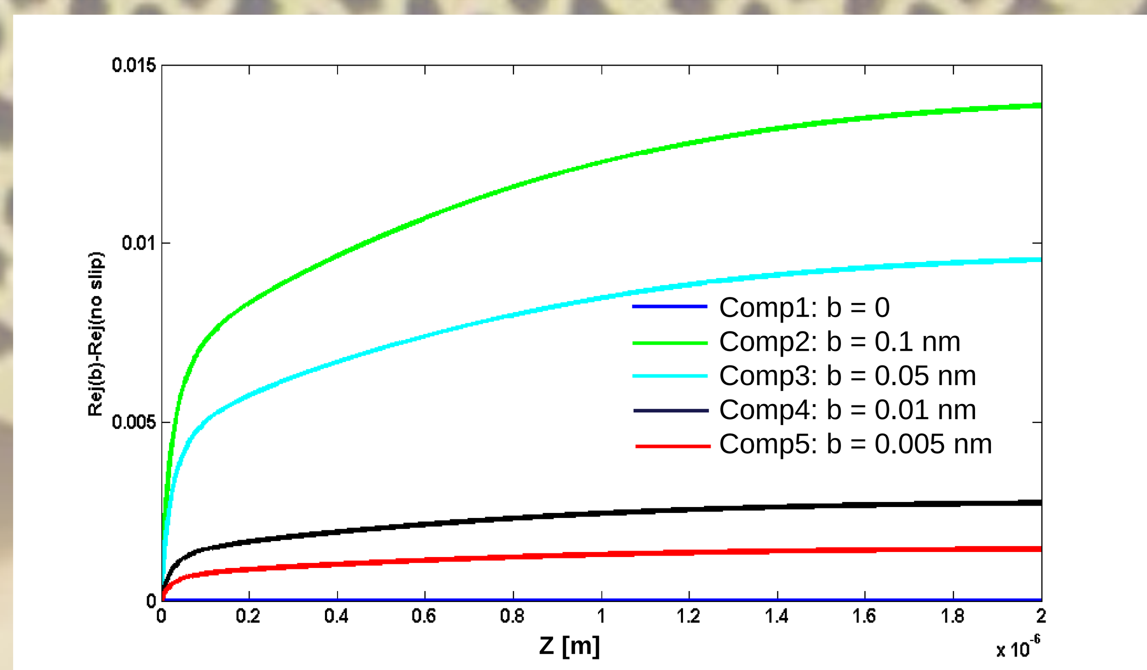


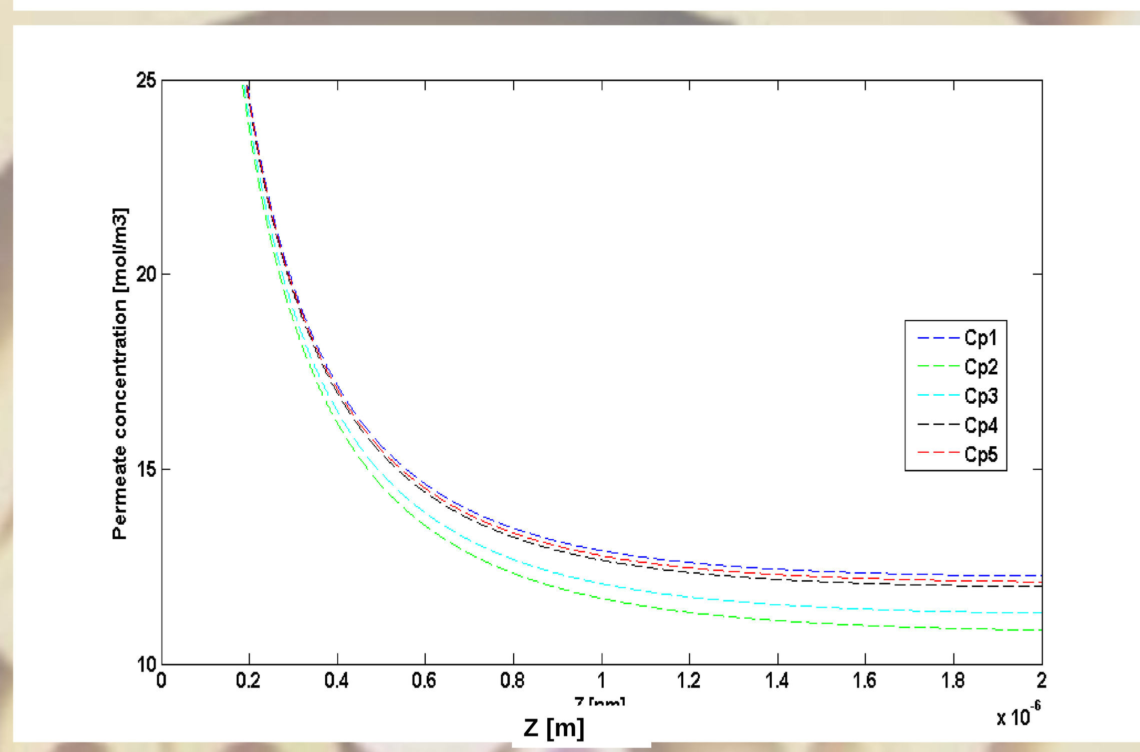


2. Glucose

Rej/ΔRej/ Conc. vs. Pore Length Z for various slip lengths b ((1-5): b= [0, 1e-10, 5e-11, 1e-11, 5e-12] m)







Conclusion

The obtained results show that by increasing the slip length which has been related to the pore size and membrane materials, the solute rejection can be increased up to approximately 5%. Concerning these results, the solute rejection can be increased by synthesis of a membrane layer with optimum conditions according to slip length.

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