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Maximizing of the Energy Generation by Pressure Retarded Osmosis

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The mass transport is analyzed in this paper in order to achieve the maximum value of the power generation applying pressure retarded osmosis. Energy generation is determined by the water transport rate which is strongly influenced by the salt flux. The effect of location of the feeding of the high-salinity solution, structure parameter and water permeability is shown and discussed. It is stated, that the outlet salt concentration should be chosen close to zero to reach water flux as high as possible. The highest value of C_m is determined by expression of $exp(J_w/k_d)$. This value should also be as low as possible to reach the value of $\Delta\pi$ as high as possible.

1. Introduction

Power generation applying renewable sources has received a lot of attention due to the decreasing supply, high cost and high greenhouse gas emission of fossil fuels (Altaee and Sharef, 2015). The future perspective of the renewable energy applications is excellently summarized by US energy administration (2013). Disadvantage of the solar and wind energy is that their performance is affected by wind and solar radiation, respectively. An integrated renewable energy-driven processes have been reviewed by Ghaffour et al. (2015). Darabina and Demichela (2013) studied the energy saving in industrial sector. One of the promising technologies which have recently been investigated intensively is the pressure retarded osmosis (PRO) (Kim and Elimelech, 2013). This technology have number of advantages which makes it suitable for application such as; it is not affected by weather conditions, it can be operated continuously, it has small foot print and it is easy to scale-up (Sharon and Reddy, 2015). Recently, the PRO process is not fully commercialized yet (Altaee and Sharef, 2015). The first pilot plant operates by this concept for energy generation is built by Statkraft Company in Norway. It uses fresh water and seawater as feed and draw solution.

The pressure retarded osmosis (PRO) generates electricity by mixing of saline and fresh water. The PRO uses the osmotic pressure difference between seawater, or concentrated brine, and fresh (e.g. river water) water to pressurize the saline stream, thereby converting the osmotic pressure of seawater into hydrostatic pressure that can be used to produce electricity. The efficiency of this process strongly depends on the operating conditions and salt permeability. The exact description of the component transfer rates is crucial for correct prediction of the specific power generated. Lee et al. (1981), as pioneer solved the diffusion-convection model and gave exactly the mass transport through an asymmetric membrane without external polarization layers. Later McCutcheon and Elimelech (2007) have developed a model which takes into account the external mass transfer resistance on the higher concentration side of the membrane. Recently Nagy (2014) developed a new model for description of the salt- and water transport. The essential of this model is that the effect of all mass transfer resistances is taken into account applying the diffusion-convection model. Applying this model the maximum value of the power density generated can be estimated under different operating conditions and membrane properties. Recently, the commercially available membranes have rather low power density, it is about 1 - 3 W/m2. Higher power density was reached under laboratory conditions, about 10 W/m2 (Chou et al., 2012). These experiments showed that the membrane properties have the greatest influence on the process efficiency.

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In this lecture it will be shown how the operating conditions have to be chosen in order to reach the maximum energy production based the simulation results on the mathematical mass transfer models developed by Nagy (2014). It will be compared the data used two different modes, namely when the draw (high salinity solution) solution is feeding on the selective membrane layer while the feed (low salinity) solution on the sponge side of membrane or vice versa. The novelty of this work is to show how the maximum value of the power density can be achieved depending on the membrane properties, on the water-, and salt permeability and its structural parameter.

2. Theory

Basic mass transport equations of every single sub-layer of the pressure retarded osmosis and direct/forward osmosis will be defined in this section based on results of Nagy's paper (2014). Note that the mass transport, through the fluid boundary layers, which can cause the external polarization layers on both sides of the membrane (ECP), have been taken into account by new, mass transport equations.

2.1 Draw, high-salinity, solution is fed on the skin layer

Taking into account all four mass transfer resistances (see Fig. 1) the salt flux for every single transport layer is given by Nagy (2014). Accordingly, the overall salt flux can be expressed as (Nagy, 2014):

$$-J_s = \beta_{ov}\left\{C_{d,s} - C_{f,p}e^{\left(J_w\left[1/k_f+1/k_d+S/D\right]\right)}\right\} \tag{1}$$

where

$$\beta_{ov} = \frac{Be^{-J_w/k_d}}{1+\dfrac{B}{J_w}\left(e^{J_w\left(S/D+1/k_f\right)} - e^{\left(-J_w/k_d\right)}\right)} \tag{2}$$

where k_d and k_f are the external mass transfer coefficients for draw and feed solution side, respectively, *B* is the salt permeability, J_w is the water flux, *S* is the structure parameter, *D* is the diffusion coefficient. The salt transport rate through the selective membrane layer can be given as (McCutcheon and Elimelech, 2007):

$$-J_s = -B\left(C_{m,s} - C_{m,p}\right) \tag{3}$$

where $C_{m,s}$ and $C_{m,p}$ are concentration on the feed side and on the sponge side of the selective layer, respectively. This concentration difference determines the water flux (J_w) which value is crucial in the value of the energy generated, namely $W=J_w\,\Delta\pi$. This concentration difference can be expressed, taking into account all mass transfer resistances, as:

$$C_{m,s} - C_{m,p} = \frac{C_{d,s}e^{-J_w/k_d} - C_{f,p}e^{J_w\left(S/D+1/k_f\right)}}{1+\dfrac{B}{J_w}\left(e^{J_w\left(S/D+1/k_f\right)} - e^{-J_w/k_d}\right)} \equiv \frac{e^{-J_w/k_d}\left[C_{d,s} - C_{f,p}e^{J_w\left(S/D+1/k_f+1/k_d\right)}\right]}{1+\dfrac{B}{J_w}\left(e^{J_w\left(S/D+1/k_f\right)} - e^{-J_w/k_d}\right)} \tag{4}$$

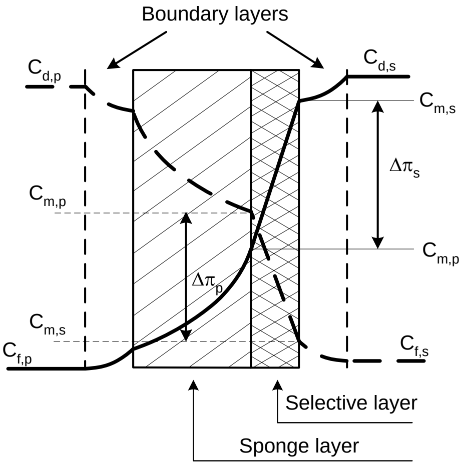

Figure 1: Schematic figure of the concentration distribution in an asymmetric PRO or FO membrane

Note that the literature neglects the effect of the external mass transfer resistance .in the feed, low-salinity solution (Tiraferri et al., 2013). One can get the value of the concentration difference on the selective layer from Eqs. (1) and (4) as follows:

$$C_{m,s} - C_{m,p} = \frac{\beta_{ov}}{B}\left[C_{d,s} - C_{f,p}e^{J_w(S/D+1/k_f+1/k_d)}\right] \tag{5}$$

The water flus then can be obtained as (Yip and Elimelech, 2011):

$$J_w = A(\Delta\pi - \Delta P) \tag{6}$$

where A denotes the water permeability, $\Delta\pi$ is osmotic pressure difference on the two sides of the selective layer, $\Delta\pi = \pi_m(C_m) - \pi_{sk}(C_{sk})$ (where $\pi = iMRT$, i denotes the dimensionless van't Hoff coefficient, M is molarity, R is gas constant, T is temperature), while ΔP denotes the hydrostatic pressure difference on the two sides of the membrane. Energy generated is product of the water flux and the hydrostatic pressure difference. It can be obtained as:

$$E = J_w \Delta P \tag{7}$$

2.2 The draw, high-salinity solution is fed on the sponge layer

The concentration distribution of this case is illustrated by broken line in Figure 1. A significant difference between these two operation methods is that in this case the salt should pass two transfer resistances before it reaches the selective layer. This circumstance can essentially affect the driving force of the water flux.

The salt transfer rate can also be given here by Eq. (1), where β_{ov} will be as:

$$\beta_{ov} = \frac{Be^{-J_w(S/D+1/k_d)}}{1 + \frac{B}{J_w}\left(e^{J_w/k_f} - e^{-J_w(S/D+1/k_d)}\right)} \tag{8}$$

The concentration difference the two sides of the selective layer is:

$$C_{m,p} - C_{m,s} = \frac{C_{d,p}e^{-J_w(S/D+1/k_d)} - C_{f,s}e^{J_w/k_f}}{1 + \frac{B}{J_w}\left(e^{J_w/k_f} - e^{-J_w(S/D+1/k_d)}\right)} \tag{9}$$

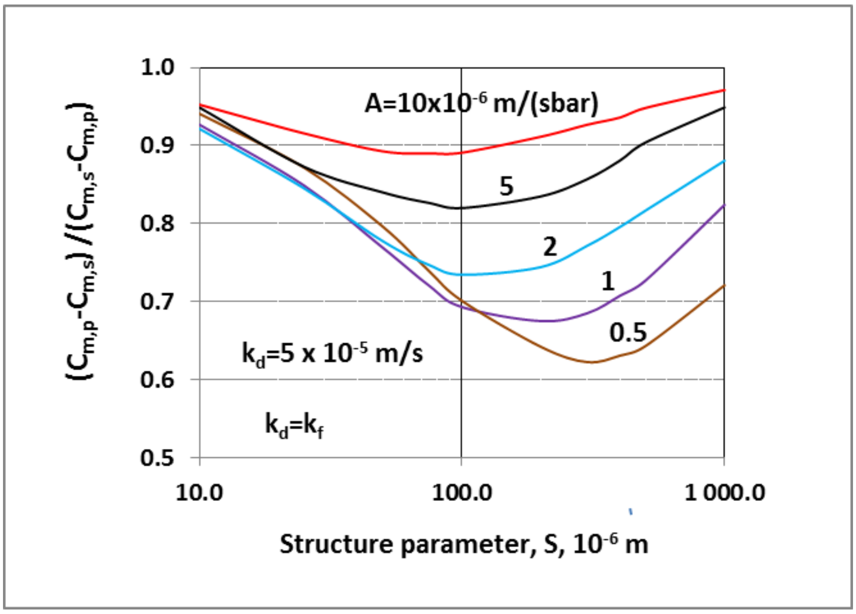

Figure 2: Effect of ratio of osmotic pressure difference of the two sides of membrane feeding the draw solution on either the sponge or the selective layer (B=1.1 x 10^{-7} m/s; C_d=58.4 kg/m^3; π_d=49.2 bar; C_f= 2.4 kg/m^3; π_f= 2.1 bar; D=1.6 x 10^{-9} m^2/s, k_d=5x10^{-5} m/s; k_d=k_f)

Note the value of $C_{m,p}$ here is the internal concentration, concentration between the sponge and the selective layers, in the asymmetric membrane.

3. Results and discussion

Energy generated is determined primarily by the water flux [Eq. (7)] which depends on two factors given in the numerator and the denominator of Eq. (4) or of Eq. (9) The driving force is modified by factors of the concentration of C_d and C_f. Let us introduce the following parameters when e.g. the high-salinity solution is fed on the selective membrane side:

$$\Delta C_s^* = C_{d,s} e^{-J_w/k_d} - C_{f,p} e^{J_w\left(S/D + 1/k_f\right)} \tag{10}$$

and

$$\vartheta = \frac{1}{1 + \dfrac{B}{J_w}\left(e^{J_w\left(S/D+1/k_f\right)} - e^{-J_w/k_d}\right)} = \frac{\beta_{ov} e^{J_w/k_d}}{B} \tag{11}$$

Similarly can these parameters be given for the case when the high-salinity solution (draw) is fed on the sponge membrane side. It will be discussed the effect of the feeding side of the draw solution and how these parameters affect the water flux.

3.1 Effect of the draw solution feeding side on the energy performance

Let us look at how the ratio of concentration difference on the two sides of the membrane, namely ($C_{m,p}$-$C_{m,s}$)/($C_{m,s}$-$C_{m,p}$), namely when the draw solution is fed on the sponge side related to that when it is fed on the selective side (Figure 2). The value of this concentration difference, and consequently the osmotic pressure difference can essentially influence the water flux (see Eq. (6). The value of the structure parameter of commercially available membranes can practically change between 100 and 600 µm. As can be seen in Figure 2, the ratio of the $C_{m,s}$-$C_{m,p}$ and $C_{m,p}$-$C_{m,s}$ is practically always less, sometimes much less, than unit. Accordingly, the water flux is higher in the case when the draw solution is fed on the side of the selective membrane layer.

An important question is how the value of ($C_{m,s}$-$C_{m,p}$) changes comparing it to the inlet and the outlet concentration difference since this value determines the osmotic pressure difference in the membrane.

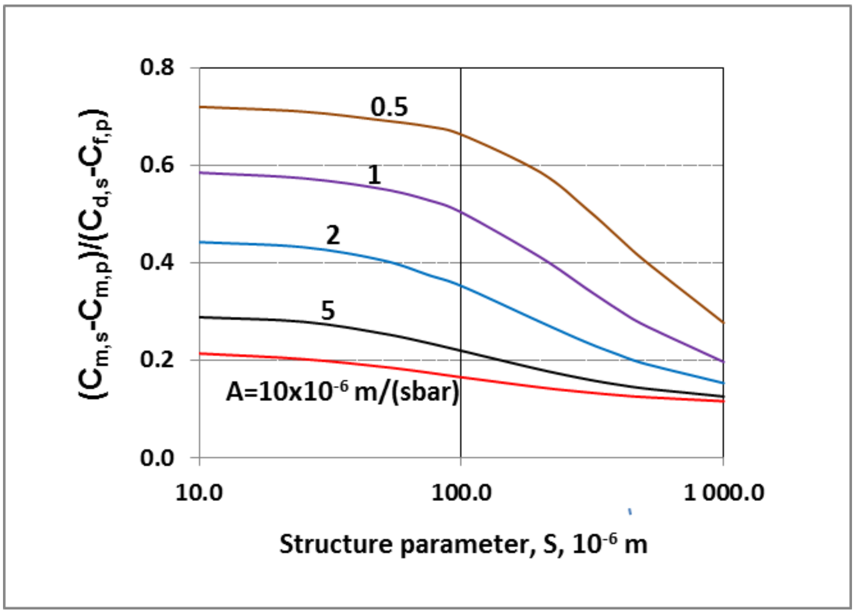

Figure 3: Change of the driving force of the water fulx as a function of structure parameter when draw solution is fed on the side of the selective layer (for parameter values see caption of Figure 2)

3.2 Driving force of water transport; change of the value of ($C_{m,s}$-$C_{m,p}$)/($C_{d,s}$-$C_{f,p}$)

Portion of the concentration fall in the selective membrane layer is illustrated in Figure 3 in the case when the high-salinity solution was fed on side of the selective layer. As can be seen this ratio depends strongly on both the value of the water permeability, namely A, and the structure parameter, S. Its value decreases significantly especially in the structure parameter range available in the commercial membranes. It can also be stated from this figure that the concentration fall on the sponge layer and on the external boundary layer is also rather high due to its low values at higher value of *S* and *A*. Accordingly, decreasing values of *S* of them can essentially increase the value of $C_{m,s}$-$C_{m,p}$, and thus, the water flux as well.

3.3 Change of real driving force, namely ΔC_S^*

The so called real driving force, namely ΔC_S^*, is defined by Eq. (10) for the case when the high-salinity solution is fed on the selective side. Figure 4 clearly shows the high portion of the ΔC_S^* in the $C_{m,s}$-$C_{m,p}$ concentration difference. Accordingly, ratio of ΔC_S^* and $C_{m,s}$-$C_{m,p}$ is close to unit, its value is somewhat higher than unit and increases with the increase of the structure parameter. It can be stated the value of ΔC_S^* should be significantly decrease in order to reach higher water flux. Only a possibility to achieve it, the value of the outlet salt concentration should be held as low as possible. The first term of Eq. (10), namely $\exp(J_w/k_d)$ should be chosen as low as possible. In reality, it is a difficult task, because both parameters strongly affect the value of the other parameter.

4. Conclusion

The concentration difference of the two sides of the selective layer, and consequently the osmotic pressure difference, $\Delta\pi$, is determined by the ΔC^* value. This value is strongly depends on the structure parameter and water permeability. The value of ϑ has a little impact on the value $\Delta\pi$ only, according to Figure. 4. The value of ΔC^* has two terms. In principle the second term of the right side of Eq. (10) can minimized by decreasing the C_f value close to zero. But the value of the first term can also highly affect the ΔC^* value (not shown here). During operation of a PRO system, the C_m value should bring as close as possible to that of C_d. The highest value of the C_m is determined by expression of $C_d\exp(J_w/k_d)$. In reality, the C_m value is always somewhat lower than its highest one. Note that the increase of J_w (as a main task of the process, raises the value of $\exp(J_w/k_d)$, thus lowers the efficiency of the energy generation.

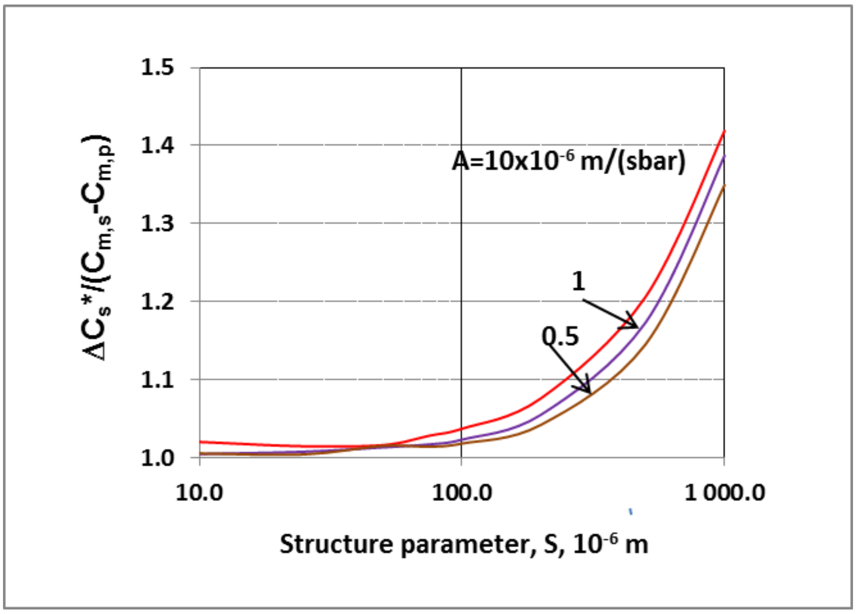

Figure 4: Change of the real driving force (parameter values are listed in cation of Figure 2)

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