Electrokinetic characterization of composite membranes: estimation of different electrical contributions in pressure induced potential measured across reverse osmosis membranes

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Abstract

Pressure induced electrical potentials across a composite polyamide/polysulfone reverse osmosis membrane and a microporous polysulfone membrane similar to the porous layer of the composite one (\(\Delta E\) and \(\Delta \phi_{PS}\), respectively) were measured with NaCl and MgCl₂ solutions at different feed concentrations. Because of the high salt rejection and the two-layered structure assumed for reverse osmosis membranes, \(\Delta E\) values do not represent the streaming potential in the active layer since other electrical potentials (diffusion potential in the active layer, streaming potential in the porous sub-layer and boundary potential) are also included. These different terms were evaluated and the streaming potential for the active and porous layers of the composite membrane, \(\Delta \phi_{st}^a\) and \(\Delta \phi_{st}^p\), were estimated under the assumption of similar streaming potential coefficient \(g = \Delta \phi_{st}^a / \Delta P\) for the porous layer of the composite membrane and the microporous polysulfone membrane (\(g_{PS}^a = g_{PS}^p\)). Differences between \(\Delta E_m\) values obtained under filtration (\(\Delta E_{mF}\), different feed and product concentrations) and dialysis conditions (\(\Delta E_{md}\), equal feed and product concentrations), for similar volumen fluxes show the influence of the porous sub-layer. A comparison between \(\Delta E_{mF}^a / \Delta P\) and active layer streaming potential coefficient, \(g^a\), is also made. Results show that the diffusion potential in the active layer is 10–15% of the total electrical potential difference across the composite membrane, while the influence of the porous layer is practically lower than 3%. The electrical potential in filtration measurements was calculated from dialysis results, once diffusion and streaming potential in the porous layer are known, and good agreement between experimental and calculated values was obtained.

Salt concentration dependences for streaming potential coefficient in porous and active layers of the reverse osmosis membrane were studied, while for the microporous polysulfone membrane the zeta potential (\(\zeta\)) was determined by the Hervolitz–Smoluchowski expression. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Composite and porous membranes; Streaming potential; Active and porous sublayers; Zeta potential; Concentration dependence

1. Introduction

Electrical and Electrokinetic phenomena play an important role in transport of electrolyte solutions across membranes [1–3]. Among other, the following
simple effects can be observed when a charged membrane is separating two isothermal saline solutions [2]:

- a streaming potential, \( \Delta \phi_{st} \), or electrical potential difference measured at both sides of a porous membrane as a result of the liquid flow through the pores under a pressure difference. The streaming potential coefficient is defined by \( g = (\Delta \phi_{st} / \Delta P)_{\Delta C = 0, I = 0} \).

- a diffusion potential, \( \Delta \phi_{dif} \), or electrical potential difference caused by a concentration gradient across the membrane, due to the different mobilities of the ions in the membrane, when \( \Delta P = 0 \) and \( I = 0 \); \( \Delta \phi_{dif} = (RT/F)[(t_+/z_+) + (t_-/z_-)] \) \( \ln(C_0/C) \), where \( t_+ \) and \( t_- \) are the cation and anion transport numbers and \( z_+ \) and \( z_- \) are their valencies.

These direct phenomena can be separately observed when single membranes are considered, and different membrane transport parameters as well as information about the electrical interactions at the membrane/solution interface can be obtained. Membrane potential is normally used to determine the distribution of charge in the membrane, while streaming potential measurements allow the investigation of the electric double layer at the membrane/solution interface by determination of the zeta potential or electrical potential at the shear plane [4–7].

However, asymmetric or composite membranes are formed by two or more sublayers with different transport properties and, in these cases, not only direct phenomena are measured since some other indirect or associated phenomena could also be included in the values determined for the whole membrane. For instance, if one sublayer presents high salt retention (as usually happens with active layers of commercial reverse osmosis and nanofiltration membranes), the permeate solution has much lower concentration than the feed solution, and a diffusion potential in this layer should arise. In general, the higher or lower contribution of the indirect effects in the values measured for a composite membrane is related to the different structures and transport properties of the sublayers forming the composite membrane. In order to avoid these effects, tangential streaming potential or streaming potential along the membrane surface (active layer) is measured lately [8–10], although this type of measurement does not allow any correlation between changes in the streaming potential (or zeta potential) due to adsorption/deposition of particles in the porous walls or on the membrane surface and other characteristic membrane transport parameters such as hydraulic permeability or ion transport numbers [11,12]. Moreover, according to Lettemann et al. [13] possible differences in the chemistry of inner and outer membrane surfaces can exist and some caution must be taken when comparison between results obtained with both different boundary conditions are made.

In this paper, pressure induced potentials for a composite reverse osmosis membrane and a microporous membrane similar to the RO porous sublayer has been measured using NaCl and MgCl\(_2\) solutions at different concentrations, which allows to study the effect on streaming potential values of different solution chemistries (type of electrolyte and concentration). From these results, and those previously obtained for membrane potential measurements [14], the streaming potential coefficient, \( g^p = (\Delta \phi_{st} / \Delta P)^{i} \), for the active and porous layers of the composite membrane \( (i = a \text{ or } p, \text{ respectively}) \) were determined assuming the same value for the streaming potential coefficient in the microporous membrane and in the porous sublayer of the composite membrane for similar external conditions \( (g^p = g^{PS}) \). Concentration dependence for the streaming potential coefficient for both membranes and electrolytes was also determined. For the microporous membrane, the zeta potential \( (\xi) \) was obtained by means of the Hemholtz–Smoluchowski equation and its dependence on salt concentration and pH was also studied.

Because of the different concentration profiles through porous sublayer of composite membranes under filtration (external control of feed solution) and dialysis (external control of both feed and permeate solutions) conditions, streaming potential for the same feed concentration and volumen fluxes (similar concentration gradient in the active layer) can present different values. Assuming for the composite membrane a simple two-layer model, good agreement between experimental and calculated streaming potential values under filtration condition was found, using for calculations the values determined in dialysis experiments as well as the diffusion and streaming potentials in the porous sublayer determined from the results previously obtained.
2. Theory

When an electrolyte solution is forced through a charged capillary by a pressure difference, \( \Delta P \), the charges in the mobile part of the double layer near the wall are carried towards one end, but the accumulation of charge sets up an electric field and, as a result of this, an electrostatic potential difference between the ends of the capillary is established, which is called ‘streaming potential’, \( \Delta \phi_{\text{st}} \). [15]. The streaming potential is an experimental parameter which could be used for electrical characterization of solid/liquid interfaces, although it not only depends on the solid surface charge, but also on the conductivity of the electrolyte solution. In order to obtain a parameter representing only the material characteristics, the zeta potential (\( \zeta \)) or electrical potential at the shear plane is commonly used [6,8,16]. For wide capillaries with low charge density, zeta potential can be obtained from streaming potential coefficient, \( g = (\Delta \phi_{\text{st}}/\Delta P) \), on the basis of the Helmholtz–Smoluchowski expression [15]

\[
\frac{\Delta \phi_{\text{st}}}{\Delta P} = \frac{\varepsilon_0 \varepsilon_r \zeta}{\chi \eta} \tag{1}
\]

\( \chi \) and \( \eta \) being the conductivity and the viscosity of the solution, respectively; \( \varepsilon_0 \) is the permittivity of vacuum and \( \varepsilon_r \) is the relative dielectric constant of the electrolyte solution. However, for narrow and/or high charge density capillaries the Helmholtz–Smoluchowski model, which is only valid for pore radius (\( r_p \)) much larger than the Debye length (\( \kappa \)), cannot be used due to possible overlapping of the double layers but also because a contribution of the fixed part of the double layer to the electrical conductivity (surface conductivity) could also exist [15]. Rice and Whitehead [17] have suggested some corrections in Eq. (1) to take into account the first point by introducing a function \( F(\kappa^{-1} r_p, \zeta) \), which is a Bessel function of first kind, while the Fairbrother and Mastin correction [15] can be used in the case of surface conductivity. However, Eq. (1) is commonly used by many authors characterizing ultrafiltration membranes and, in that cases, an ‘apparent zeta potential’, \( \zeta_{\text{ap}} \), is determined, which is used for comparison among membranes with similar characteristics [18,19].

Microfiltration membranes are usually represented as a bunch of capillaries and the electrokinetic characterization is commonly carried out by zeta potential values determined by Eq. (1), [15]. However, most of the membranes used in pressure-driven separation systems are composite membranes which, in the most simple case, are represented by a bilayer model consisting in a series association of two homogeneous elements, active and porous sublayers, with different transport properties [20]. It is normally assumed that the thin and dense active layer control the water and salt fluxes, while the porous and thick sublayer provides membrane stability. In the case of reverse osmosis or nanofiltration membranes, with high salt rejection and very narrow pores, not only the overlapping of the double layer but also the concentration profile through the dense active layer should be considered. For these membranes, the pressure induced potential \( \Delta E \) does not correspond exactly to the streaming potential, which cannot be directly obtained from experiments, since other different potentials are also included in \( \Delta E \) values.

Fig. 1 shows the schematic diagram of the concentration profiles in a reverse osmosis membrane under a pressure difference for filtration (A) and dialysis (B) conditions. As can be seen, the effect of a pressure difference applied to the membrane causes a volume flux but also concentration gradients in one of both sublayers of the composite membrane, depending on the external conditions, which also originates a diffusion potential (\( \Delta \phi_{\text{dif}} \)). In Fig. 1A, it was assumed that the reflection coefficient in the porous sublayer, \( \sigma_p \), is zero, which means that no concentration gradient through this layer exists (\( C_i = C' \)).

Taking into account Fig. 1, it can be observed that the electrical potential difference, \( \Delta E \), measured at both sides of a composite reverse osmosis membrane due to a pressure difference, \( \Delta P \), does not correspond exactly to a streaming potential, since other terms have to be considered [21]. Depending on the external conditions, \( \Delta E^E (\Delta E^F \text{ or } \Delta E^D) \), respectively) can be expressed as the sum of the following individual potentials in the membrane, the solution and the interface:

\[
\Delta E^E = \Delta \phi_{\text{el}} + \Delta \phi_{\text{pol}} + \Delta E_m^F = \Delta \phi_{\text{el}} + \Delta \phi_{\text{pol}}^F + \Delta \phi_{\text{bound}} + \Delta \phi_{\text{dif}} + (\Delta \phi_{\text{pol}}^F) + \Delta \phi_{\text{el}} \tag{2}
\]
$\Delta E^D = \Delta \phi_{el} + \Delta \phi_{\text{dif}}^{\text{pol}} + \Delta E_{m}^D = \Delta \phi_{el}(P) + \Delta \phi_{\text{dif}}^{\text{pol}}$

$+ \Delta \phi_{\text{bound}} + \Delta \phi_{\text{dif}}^{p} + (\Delta \phi_{\text{el}})^* + \Delta \phi_{\text{st}}$

$+(\Delta \phi_{\text{st}})^*$

(3)

where $\Delta \phi_{el} = \Delta \phi_{el}(C) + \Delta \phi_{el}(P)$ is the electrode potential, which consists of two parts due to differences in concentration and pressure between both compartments; $\Delta \phi_{\text{dif}}^{\text{pol}}$ is the diffusion potential in the electrolyte solution due to the concentration polarization at the feed solution/active layer interface and $\Delta \phi_{\text{bound}}$ represents the boundary potential at the membrane/solution interface, which is due to the different concentration of ions in the membrane and the electrolyte solution. In the membrane itself ($\Delta E_{m}^i$), different electrical potentials can be found in both active (a) and porous (p) layers according to Fig. 1A: a streaming potential caused by the pressure difference, $(\Delta \phi_{\text{el}})^*$, a diffusion potential due to the concentration difference through the active layer, $\Delta \phi_{\text{dif}}^{a}$, and the streaming potential in the porous layer, $\Delta \phi_{\text{st}}^{p}$; however, under dialysis conditions (Fig. 1B), the contribution of diffusion potential due to the concentration gradient in the porous layer have to be also considered. It should be pointed out that $(\Delta \phi_{\text{el}})^*$ and $(\Delta \phi_{\text{st}})^*$ in Eqs. (2) and (3) do not represent exactly the streaming potential in active and porous sublayers at a given concentration, since the condition $\Delta C = 0$ is not fulfilled, but they may be considered as a kind of average streaming potential values for the interval of concentrations between $C'$ and $C_i$.

Some of the terms indicated in Eqs. (2) and (3) can easily be evaluated:

1. for the pressure dependent part of the electrode potential, Spiegler [22] indicated a correction factor given by: $-1.61 \times 10^{-4} \Delta P$ (cm$^3$/A s); in our case, it represents a value of 0.13 mV at the highest pressure difference.

2. the increase in the concentration values due to the concentration polarization at the feed solution/active layer interface was obtained by means of the program indicated in [23], which gives for $\Delta \phi_{\text{dif}}^{\text{pol}}$ the highest value of 0.07 mV.

These results indicate that the influence of both $\Delta \phi_{el}(P)$ and $\Delta \phi_{\text{dif}}^{\text{pol}}$ in $\Delta E^F$ values can be practically neglected when they are compared with the experimental values. On the other hand, the concentration dependent part of the electrode potential is given by the following expression (diluted solutions): $\Delta \phi_{el}(C) = (RT/F) \ln(C'/C''_p)$, and its values can be calculated for each pair of feed and product concentrations ($C'$, $C''_p$).

Assuming that for similar volumen fluxes the concentration profiles in the active layer for filtration and dialysis measurements are the same, differences between $\Delta E_{m}^F$ and $\Delta E_{m}^D$ values basically represent the contribution of the diffusion potential in the porous layer, and the electrical potential difference directly related to the characteristic properties of reverse osmosis or nanofiltration membranes (two layer structure and high ion exclusion), $\Delta E_{m}^D$, can be expressed (if $\Delta \phi_{\text{st}}^{p} \equiv (\Delta \phi_{\text{st}})^*$) as:
\[
\Delta E_m^F = \Delta \phi_{\text{bound}} + \Delta \phi_{\text{diff}}^a + (\Delta \phi_{\text{st}}) + \Delta \phi_{\text{st}}^P \\
\cong \Delta E_m^D + \Delta \phi_{\text{diff}}^P
\] (4)

\[
\Delta E_m^D = \Delta \phi_{\text{bound}} + \Delta \phi_{\text{diff}}^a + (\Delta \phi_{\text{st}}) + \Delta \phi_{\text{st}}^P \\
+ \Delta \phi_{\text{diff}}^P + (\Delta \phi_{\text{st}}^P)^* \] (5)

although differences between \( \Delta \phi_{\text{st}}^P \) and \((\Delta \phi_{\text{st}}^P)^*\) values can exist in some cases.

3. Experimental

Two different membranes from Dow Denmark Separation Systems (DDSS) were used: a composite polyamide/polysulfone reverse osmosis membrane (HR 95), and a microporous polysulfone membrane (PS) similar to the porous sublayer of HR 95; in both cases, the polymeric membranes were deposited on a non-woven support and the thickness for the whole system was \((168 \pm 2) \mu m\). For the HR 95 membrane the salt rejection ranges between 80 and 98%, depending on salt concentration and pressure, and the hydraulic permeability, \( L_p \), was around \(8 \times 10^{-12} \text{ m/s Pa} \) while for the PS membrane \( L_p \cong 10^{-10} \text{ m/s Pa} \).

The equipment was described elsewhere \([12,14]\), and the experiments were carried out in a cross-flow test cell made of acrylic with NaCl and MgCl\(_2\) aqueous solutions at a constant temperature of \((25.0 \pm 0.2) ^\circ C\). In order to avoid membrane compaction during measurements, the membranes were maintained at the highest pressure for 4 h with distilled water. Feed concentration ranged between \(10^{-3} \text{ N} \) and \(5 \times 10^{-2} \text{ N}\). Solute concentrations of the feed \((C')\) and product \((C'')\) were determined by conductivity measurements (Radiometer CDM-3 conductivity meter). The electrical potential difference between both half-cells, \( \Delta E \), was measured with Ag/AgCl electrodes, which were placed in the center of each half-cell, and connected to a high impedance voltmeter. \( \Delta E \) values were taken when the system reached steady state, this means, when the values became practically independent of time. Pressure values ranged from 1.5 to 9 atm, and the speed of the circulating solution at the high pressure side was \(125 \text{ cm/s}\) approximately. Measurements with the composite membrane were carried out with its active layer facing the high pressure side.

For comparison, measurements under dialysis condition, this means fixing both feed and permeate solutions, were also carried out. In this case, the concentration of the permeate side, \(C''\), (low pressure compartment) was always maintained at the same constant value that feed solution \([12]\). The permeate tank had a capacity of \(300 \text{ cm}^3\) and the pump output was \(2.21/\text{min}\). To ensure similar concentration profiles in the membrane under both different external conditions, measurements were carried out for similar values of the volumen flux.

4. Results and discussion

Fig. 2A and B shows the membrane part of pressure-induced potential, \( \Delta E_m \), as a function of the applied pressure difference, \( \Delta P \), for HR 95 and PS membranes at two feed concentrations \((0.005 \text{ and } 0.02 \text{ N})\) with \(\text{NaCl}\) and \(\text{MgCl}_2\) solutions, respectively. As can be seen from Fig. 2, \(\Delta E_m\) values depend on both concentration and electrolyte. The influence of the porous layer in \(\Delta E_m\) values measured with the HR 95 membrane is also shown in Fig. 2 by comparison of pressure-induced potentials under filtration and dialysis conditions \((\Delta E_m^F\) and \(\Delta E_m^D\)), for the same external concentrations and similar volumen flow (this means, similar internal concentration \(C_i\)). At low pressures \((\Delta P<5 \text{ atm})\), \(\Delta E_m^D\) values hardly differ from \(\Delta E_m^F\), but some differences were obtained at the highest pressures, when the permeate (or intermediate) concentration \(C_i\) has very low values. This kind of results was reported by Demisch and Pusch using asymmetric cellulose acetate membranes \([21]\). Although straight lines were obtained in all cases, only for the PS membrane the measured \(\Delta E_m\) values represent the streaming potential \((\Delta E_m\text{(PS)}=\Delta \phi_{\text{st}}^{\text{PS}}))\) and the streaming potential coefficient, \(g_{\text{PS}} = (\Delta \phi_{\text{st}}^{\text{PS}} / \Delta P)\), can be determined from the slopes of these straight lines; however, for the composite HR 95 membrane other potentials are also included in \(\Delta E_m\) values, which can have significant contributions even at \(\Delta P=0\) (boundary potentials) under both filtration and dialysis conditions, as can also be seen in Fig. 2.

Streaming potential coefficient-concentration dependence for the PS membrane is shown in Fig. 3. As was previously reported \([24]\), the PS membrane presents a small negative charge due to the adsorption of \(\text{Cl}^-\) ions, because of which \(g_{\text{PS}}\) values tends to zero at high concentrations, when the effect of the small
charge can be neglected. Assuming the validity of the
Helmholtz–Smoluchowski equation for the porous PS
membrane, the zeta potential was obtained by means
of Eq. (1) and its dependence on salt concentration
is also shown in Fig. 3. Results show that
values are practically independent of concentration, but they
depend on the electrolyte, and the following average
values were obtained:
\[ \zeta_{PS}^{NaCl} = -9.9 \pm 0.6 \text{ mV} \]
and
\[ \zeta_{PS}^{MgCl_2} = -6.4 \pm 0.5 \text{ mV} \]

In a previous paper [14], diffusion potentials for
both HR 95 and PS membranes and electrolytes were
measured in a different set of experiments (when
\[ \Delta P = 0 \]); from these results, transport numbers for the
active and porous layers of the composite membrane
were determined and their values at different salt con-
centrations were indicated. If \( t^a \) values are known, the
diffusion potential in the active layer for each pair of
concentrations \( (C', C_i) \) can be obtained. Results
show that the contribution of the active layer diffusion
potential to the electrical potential difference deter-
mined for the whole composite membrane ranges
between 10 and 15%, depending on the electrolyte
solution. Subtracting \( \Delta \phi_{el} \), \( \Delta \phi_{pol} \) and \( \Delta \phi_{dif} \) from the
measured \( \Delta E^F \) potentials, \( \Delta E_{m}^* \) was obtained:
\[ \Delta E_{m}^* = \Delta \phi_{bound} + (\Delta \phi_{el})^* + \Delta \phi_{dif}^P \]  

In order to determine the streaming potential co-
efficient in the active layer of the composite HR 95
membrane the contribution of the polysulfone sub-
layer \( \Delta \phi_{dif}^P \) must be evaluated and it can be done
if the streaming potential coefficient and the effec-
tive pressure difference in the porous sublayer \( (g^P, \Delta P_{ef}, \text{ respectively}) \) are known. It was assumed
that \( g_{PS}^{PS} = g^P \), and the effective pressure in the porous
layer was determined by comparison of the volume
flux \( (J_i) \) through both HR 95 and PS membranes, for
each external pressure and feed concentration, and tak-
ing into account its continuity across the composite
membrane \( (J_{HR} = J_i^* = J_i^P) \). Then, the streaming
potential values in the polysulfone sublayer, $\Delta \phi_{st}^P = g_{PS}^p (C^0) \Delta P_{ef}$, at each concentration $C^0$ (the concentration of the permeate in the measurements with the composite membrane) can be determined by interpolation in the results shown in Fig. 3. Although $C^0$ values are very low due to the high salt retention of HR 95 membrane, the porous layer streaming potential contribution to the total membrane electrical potential difference is practically lower than 3% (except for the lowest concentration which is around 5%), due to the small pressure difference across this layer.

Subtracting $\Delta \phi_{st}^P$ values from $\Delta E_m^*$ we have:

$$\Delta F = \Delta E_m^* - \Delta \phi_{st}^P = \Delta \phi_{bound}(C) + (\Delta \phi_{st}^a(P))^*$$

(7)

on the right-hand side of Eq. (7) the dependence of each term is explicitly indicated. Since the boundary potential is independent of pressure, its value at a given concentration is obtained from the interception (when $\Delta P=0$) in the plot of $\Delta F$ versus $\Delta P$, while the slope gives the active layer streaming potential coefficient.
Variation of the boundary potential with the external salt concentration is shown in Fig. 4. At low concentrations some differences in $\Delta \phi_{\text{bound}}$ values depending on the electrolyte were found, which can be due to the higher salt rejection for MgCl$_2$ solution at these concentrations, but a logarithmic decrease in $\Delta \phi_{\text{bound}}$ values when the salt concentration increases was obtained for both electrolytes.

Concentration dependence for the active layer streaming potential coefficient, $g^a$, is indicated in Fig. 5 for both electrolytes. For comparison, $\Delta E_m^F/\Delta P$ values obtained directly from the slopes of the straight lines shown in Fig. 2, this means, without corrections for other possible potentials included in $\Delta E_m$ values, are also indicated in Fig. 5. As can be seen from this picture, average differences between $g^a$ and $\Delta E_m^F/\Delta P$ values around 13% were obtained with both electrolytes.

The reliability of the parameters previously determined for active and porous sublayers of the HR 95 membrane can be tested by comparing $\Delta E_m$ and $\Delta E_m^D$ values. According to Eqs. (4) and (5), the only difference between pressure-induced potential under filtration and dialysis conditions is the diffusion potential in the porous layer (assuming $(\Delta \phi_{\text{ps}}^P)^* = \Delta \phi_{\text{ps}}^P$ which can be determined when $\Gamma_{\text{ps}}^C$ and $C_i$ values are known. A comparison of experimental $\Delta E_m^D$ data with those calculated by means of Eq. (4) from dialysis experimental results by subtraction of the diffusion potential in the porous layer, this means: $\Delta E_m^D(\text{cal}) = \Delta E_m^D(\text{exp}) - \Delta \phi_{\text{ps}}^P$, is shown in Fig. 6. As can be seen from this picture, quite good agreement between experimental and calculated values was obtained, and only small differences were found at low concentrations and high pressure gradients, when $C_i$ is very low, which is attributed to differences between $\Delta \phi_{\text{ps}}^P$ and $(\Delta \phi_{\text{ps}}^P)^*$ in such conditions.

5. Conclusions

Pressure-induced potentials across a composite polyamide/polysulfone reverse osmosis membrane and a microporous polysulfone membrane similar to its porous support were measured with NaCl and MgCl$_2$ solutions at different concentrations.

- Contribution of the porous sublayer to the pressure induced potential of the composite membrane was estimated assuming for this sublayer the same values that those determined for the microporous polysulfone membrane under similar external conditions. Results show that this contribution is practically lower than 3% of the electrical potential difference determined for the whole membrane. Zeta potentials for the polysulfone membrane as a function of salt concentration were obtained; results show that zeta potential values are practically independent of concentration, but they depend on electrolyte.

- Contribution due to the diffusion potential in the active layer was also estimated, and it ranged between 10 and 15% of the total electrical potential difference across the composite membrane.

- Concentration dependence for the active layer streaming potential coefficient shows a decrease of $g^a$ values when the concentration increases, for both electrolytes. A comparison of $g^a$ values with those directly determined from pressure-induced potential ($\Delta E_m^F/\Delta P$) shows important differences (around 13%).

- Differences in pressure-induced potential measured under filtration and dialysis conditions are attributed to the influence of the porous sublayer. These results were used for testing the previously estimated parameters, assuming for the composite membrane a simple two-layer model.

6. Nomenclature

- $C$: concentration of solute
- $C_i$: intermediate concentration
- $E^D$: electrical potential under dialysis conditions ($C'=C''$)
- $E^F$: electrical potential under filtration conditions ($C'\neq C''$)
- $F$: Faraday constant
- $g$: streaming potential coefficient ($\Delta \phi_{\text{st}}/\Delta P$)
- $J_v$: volume flux
- $\Delta P$: transmembrane pressure difference
- $\Delta P_{\text{ef}}$: effective pressure difference across the porous layer
- $t_+/t_-$: cation/anion transport number
- $R$: gas constant
- $z+/z_-$: cation/anion valency
Greek letters

\begin{align*}
\Delta \phi_{\text{bound}} & \quad \text{boundary potential} \\
\Delta \phi_{\text{el}} & \quad \text{electrode potential} \\
\Delta \phi_{\text{dif}} & \quad \text{diffusion potential} \\
\Delta \phi_{\text{dif}}^{\text{pol}} & \quad \text{diffusion potential in the electrolyte solution due to concentration-polarization} \\
\Delta \phi_{\text{dif}}^{i} & \quad \text{diffusion potential in the active/porous layer of the composite membrane (i=\text{a/p})} \\
\Delta \phi_{\text{st}}^{i} & \quad \text{streaming potential in the active/porous layer of the composite membrane (i=\text{a/p})} \\
\Delta \phi_{\text{PS}} & \quad \text{streaming potential in the polysulfon membrane} \\
\end{align*}

Superscripts

\begin{align*}
a & \quad \text{active layer} \\
P & \quad \text{porous layer} \\
\text{PS} & \quad \text{polysulfon membrane} \\
' & \quad \text{solution in contact with the active layer} \\
'' & \quad \text{solution in contact with the porous layer} \\
\end{align*}

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