STREAMING POTENTIALS OF NUCLEPORE MEMBRANES
BY THE ELECTRIC WORK METHOD

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Abstract—Streaming potential measurements have been carried out on NUCLEPORE polycarbonate
membranes with pore diameters between 0.015 and 1.0 μm, equilibrated in KCl or NaCl solutions. Three
types of membrane behavior can be seen from the variation of \( \Delta E / \Delta p \) with time. Concentration
polarization across the membrane is significant for a membrane with a pore diameter of 0.015 μm. For
membranes with pore diameters between 0.015 and 0.6 μm, the \( \Delta E / \Delta p \) rises rapidly towards a stable
value when a pressure difference is applied. In membranes with pore diameters between 0.6 and 1 μm, the
high liquid velocity alters the interactions at the wall during the course of measurement, and this is
reflected in a decreasing \( \Delta E / \Delta p \) with time. Some results obtained by varying pore radius and
concentration agree with previous studies. Our results, as well as results reported in the literature,
are interpreted in terms of a new theoretical method; the electric work method. Electric work is
produced for positive liquid velocity, consistent with momentum production at the membrane wall
during the measurement. A relation between the magnitude of layer where momentum transfer takes
place and the streaming potential can be applied. Momentum transfer at the membrane wall may
extend about 0.1 μm into the pore.

Key words: electric work method, streaming potential, Nuclepore membranes

1. INTRODUCTION

Streaming potentials of the commercially available
NUCLEPORE membranes have been reported
for various conditions by Martinez and coworkers[1-2,
4]. The pores of these polycarbonate membranes
have been well characterized by Hernandez et al.[3].
One purpose of the present work is to report stream-
ing potential measurements on such membranes with
more details than before. The following cell is used:

\[
\text{Ag(s)} \mid \text{AgCl(s)} \mid \text{MCl(c, aq)p}_1 \mid \text{mem} \mid \text{MCl(c, aq)p}_2 \mid \text{AgCl(a)} \mid \text{Ag(s)}
\]

AgCl(a) \mid Ag(s) [a]

The electrolyte is an alkali chloride (Na or K), and
mem is the porous membrane. Electrons are passing
from left to right in the external circuit. While Mar-
tinez and coworkers[1-4] used additional salts with
this system, we have studied a wider range of pore
radii than they have. The potential difference, \( \Delta E \),
divided by the pressure difference is the streaming
potential, \( \nu \), of the cell:

\[
\left( \frac{\Delta E}{\Delta p} \right)_{j=0} = \nu
\]

In our experimental procedure we record the time-
evolution of \( \Delta E / \Delta p \) of cell [a] as a function of a
(constant) applied pressure difference \( \Delta p = p_1 - p_2 \)
in addition to the steady state \( \Delta E \). This means that a
good control of the steady state value is obtained.
Our experimental procedure can be regarded as an
extension of a method applied to ion-exchange
membranes[5].

A new theory of electrokinetic phenomena, the
electric work method[6], has been presented in a
separate paper.

2. PRINCIPLES

The electric work method[6], which is a wholistic
method, gives the following streaming potential of a
cell with a membrane having cylindrical pores:

\[
\left( \frac{\Delta E}{\Delta p} \right)_{j=0, \Delta e=0} = \frac{\tau \delta r}{2 \eta} \left[ 1 - \frac{2 \delta r}{3 r_0} + \frac{1}{6} \left( \frac{\delta r}{r_0} \right)^2 \right] + \frac{\sigma \delta r}{3 \eta} \frac{r_0^2}{r^2} \frac{dr}{dx}
\]

The differential transverse momentum transference
factor, \( \tau \), and the longitudinal momentum trans-
ference factor, \( \sigma \), are defined through the equation of
motion for the liquid (see equation (4) below and
Ref. [6], for further details). The \( \tau \) is a function of
the distance \( r \) from the axis (see below), Furthermore, \( \eta \)
is the viscosity of the flowing liquid, \( r_0 \) is the pore
radius, \( \delta r \) is the interface layer in the pore. This layer

169
is active in momentum production. The pore axis is placed in the x-direction.

In equation (2), the quantity \( \tau \) has the following meaning\(^6\): \( \tau = \left[ \frac{\partial \tau}{\partial r} \right]_r \). For a cylindrical pore the equation of motion is:

\[
\frac{du}{dr} = \frac{\eta \left( \frac{du}{dr} \right) r}{r} + \frac{\Delta p}{r} - \left( \frac{\partial \tau}{\partial r} + \frac{\partial \tau}{\partial x} \right)
\]  

(3)

here \( u \) is the liquid velocity, \( \rho \) is the mass density, \( t \) is the time and \( j \) is the current density. Equation (3) shows the reversibility character of the transference factors. When \( \Delta p \) is applied, the construction of the cell with its electric circuit makes possible a split of velocities of the moving solvent and the salt in the membrane. The motion of the salt is such that the velocities of cations and anion differ, without violating local electroneutrality. This gives an electric current which in turn produces an external electric potential at the electrodes, the streaming potential. In the reverse situation, the electric current can produce a movement of solution. The work associated with the reversible transfer of momentum and thus the kinetic energy of neutral components gives the major contributions to the streaming potential, the question of electrostatic potential inside matter we leave aside.

Assume first that the pore radius \( r_0 \) is large compared to the interface layer (and again that the longitudinal effect is negligible). Equation (2) then reduces to:

\[
v_{dr \times r_0} = \frac{\tau \partial r}{2\eta}
\]  

(4)

The wall condition is little influenced by the bulk in this case. We may then expect that the streaming potential is independent of \( r_0 \). For smaller pores, the momentum converting zone of the pore filled with liquid extends across all the pore, so that \( \partial r = r_0 \). We then obtain from equation (2), still neglecting the longitudinal effects:

\[
v_{r_0 \rightarrow 0} = \frac{\tau \partial r}{4\eta} = \frac{\tau r_0}{4\eta}
\]  

(5)

This equation expresses that the streaming potential goes to zero linearly as \( r_0 \) goes to zero. The limit value is finite, however, partly due to the longitudinal effect, partly due to the fact that \( r_0 \) does not reach zero on the nanometer scale.

The variation of \( v \) with \( r_0 \) is explained in the conventional theory by constant bulk electric conductivity for large \( r_0 \), and an increasing importance of the pore surface conductivity as the radius decreases. This explanation is not possible in the electric work method, as the electric conductivity does not enter equations (2), (4) and (5), see Ref. [6].

### 3. EXPERIMENTAL

#### Solutions and electrodes

Solutions and electrodes were prepared according to procedures reported previously\(^5\). The relative potential of electrodes was no more than \( \pm 20 \mu V \) throughout the experiment. Nitrogen bubbling of the solutions was always used to remove \( O_2(g) \) which may affect the electrodes. It is known that the streaming potential is sensitive to pH changes below pH 6\(^7\). Nitrogen bubbling to remove \( CO_2(g) \) was sufficient to keep pH above this level in the dilute solutions, while the corresponding hydroxide was added to keep the pH of the concentrated solutions.

#### Membranes

The NUCLEPORE polycarbonate membranes are homogeneous so-called straight-through membranes. Membrane properties are given in Table 1. The pores are said to be close to uniform and perpendicular to the membrane surface, but deviations from producer characteristics exist\(^3, 8-10\). These are mainly due to multiple and not perpendicular pores according to Hernandez et al.\(^3\). We have confirmed this by scanning electron micrographs especially for the large pore diameters (Fig. 1). Despite such deviations, this membrane is still more suitable in practice than cellulose acetate membranes, which contain a network of pores.

The two sides of the membranes are not equivalent. For several membranes the measurements gave streaming potentials for the two sides which differed by 10%. Scanning electron micrographs\(^8\) revealed that the pore openings differ, the shiny side openings being more regular than those of the dull side. The shiny side was therefore used against the highest pressure, as recommended by the producer. Membranes were equilibrated in the solution of the experiment at least 72 h before use.

<table>
<thead>
<tr>
<th>Pore diameter ( d_p ) by producer ( /\mu m )</th>
<th>Mean pore diameter ( /\mu m )</th>
<th>Multiple pores ( % )</th>
<th>Thickness ( /\mu m )</th>
<th>ml min cm(^{-2} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.015</td>
<td>0.015</td>
<td>0.05</td>
<td>0.05</td>
<td></td>
</tr>
<tr>
<td>0.1</td>
<td>0.0871 ± 0.019 ([4])</td>
<td>6.4 ([4])</td>
<td>200</td>
<td>4.0</td>
</tr>
<tr>
<td>0.2</td>
<td>0.376 ± 0.083 ([4])</td>
<td>20.2 ([4])</td>
<td>2.5</td>
<td>70</td>
</tr>
<tr>
<td>0.6</td>
<td>1.7</td>
<td>115</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.0</td>
<td>11</td>
<td>250</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The permeability is reported for a pressure difference of 0.7 bar.
Streaming potentials of nuclepore membranes

Fig. 1. Scanning electron micrographs of NUCLEPORE membranes with pore diameter 1.0 μm, showing the frequency of multiple pores.

Apparatus

The streaming potential cell for ion exchange membranes was reported previously[5]. In order to obtain reproducible results for membranes with larger pore diameters, the cell was modified as shown in Fig. 2. The volume of one cell chamber was 140 cm³, about a tenfold increase from the cell used with ion-exchange membranes[5]. A teflon slit (Du Pont) having a single pore of diameter 5 mm supported the membrane on the high pressure side, while a supporter with pores of diameter 1 mm were used on the low pressure side. The pressure difference was created by application of N₂(g) to one compartment, while the other compartment was kept at atmospheric pressure. The pressure difference can be controlled by a MKS pressure transducer 223BD with control valve 0248 A and controller 250C-1-D. Possible variations in Δp are 100 Pa to 0.1 MPa.

The emf values, measured by a digital voltmeter Keithley 617 A, were processed by an IBM computer model XT 286. Readings were obtained every 300 ms, when necessary.

Procedure

Cell and membrane mounting, pressure pulse application and base line recording has been described previously[5]. With small and intermediate pores (pore diameter <0.4 μm), the pressure
pulse duration was up to 200 s. The maximum pressure difference may be as high as 100 kPa in this case, but lower pressures were used in practice. With larger pores present, $\Delta p$ was varied between 0.2 and 3 kPa, and the pulse duration was normally 2–3 s.

About 10 different pressures were applied to obtain the function $E = f(\Delta p)$. The streaming potential was calculated using linear regression on this curve. With the exception of very few cases, the line passed through origin within one standard deviation of $E_{\Delta p=0}$. This experimental procedure combined with the practical cell adjustments described above allowed for results more reproducible than reported before.

4. RESULTS

Consistency of the method

A positive emf was obtained for $\Delta p = p_1 - p_2 > 0$ in cell[a]. Identical results were obtained with the membrane pore diameter 0.05 $\mu$m, for the new and the old cell. Furthermore, the streaming potential for a membrane equilibrated in 0.001 M NaCl was 0.991 ± 0.075 $\mu$V Pa$^{-1}$, which agrees very well with the results obtained by Martinez et al. (1.05 ± 0.1 $\mu$V Pa$^{-1}$)[2]. We therefore consider all results reliable within the uncertainty given.

A sufficiently large diameter of the hole in the teflon supporter is crucial for the results. A test of the teflon supporter alone showed that a hole of diameter 0.3 mm caused a considerable streaming potential by itself ($\nu = 3.38 \times 10^{-2} \mu$V Pa$^{-1}$ without any membrane in the cell for a 0.03 M NaCl solution). This is slightly higher than observations for the NUCLEPORE membranes at the same salt concentration. The 1 mm slits did not show any influence on the measurements.

Emf as a function of time

The emf rose within seconds as soon as $\Delta p$ was applied (see eg Fig. 4). Three different performances were observed, for membranes with the small pore diameter $d_0 = 0.015 \mu$m, with intermediate pore diameters $0.05 \mu$m $\leq d_i \leq 0.4 \mu$m, and with large pore diameters, $d_o \geq 0.4 \mu$m.

For the smallest pore diameter ($0.015 \mu$m), the emf was a linear function of $\sqrt{t}$ (Fig. 3). This behavior is similar to our observation on ion-exchange membranes[5]. We expect that $d_o = 0.015 \mu$m is close to an upper limit of such behavior. The emf giving the streaming potential was obtained by extrapolations to $t = 0$ (see Fig. 3).

For the intermediate pores the emf reached a constant value after 10–20 s (Fig. 4). The magnitude of $\Delta p$ did not affect the streaming potentials.

For the large pore diameters, a stable or maximum value of $E$ was obtained within 1 s, and used for determination of the streaming potential. Reproducible maximum values were only obtained using short pressure pulses (3–4 s) of comparatively small magnitude (see Figs 5 and 6). Longer $\Delta p$ pulses and $\Delta p > 2$ kPa gave a decreasing emf (see Fig. 6). The maximum value was recovered after re-equilibration, however.

Streaming potentials

All plots of $E$ vs. $\Delta p$ had correlation coefficients of at least 0.9999, which is better than previously reported. The streaming potential was normally reproducible within ±2% for the same membrane.
Streaming potentials of nuclepore membranes

When \( d_o < 0.4 \mu m \). The deviation between different membrane disks was \( \pm 5\% \). This can be expected from the variation in \( d_o \) (see Table 1). The values for membranes with \( d_o > 0.4 \mu m \) were reproducible only within \( \pm 10\% \). Membranes are said to give laminar flow when \( 1 \gg d \). The 0.6 \( \mu m \) and 1 \( \mu m \) membranes must be considered as a border-line cases in this respect (see Table 1), resulting in larger deviations for \( v \).

Streaming potentials for 0.03 M KCl and NaCl are listed in Table 2 and plotted in Fig. 7 as a function of membrane pore diameter. Results for 0.001 M KCl are also listed in Table 2, and plotted in Fig. 8 together with values taken from the literature[2].

The main results of the plots of Fig. 7 (0.03 M KCl and NaCl) are relatively constant values for \( v \) for all pore diameters, \( 2.6 \pm 0.2 \times 10^{-2} \mu V \, Pa^{-1} \) (for KCl) and \( 2.0 \pm 0.2 \times 10^{-2} \mu V \, Pa^{-1} \) (for NaCl). In the 0.001 M KCl-solution, a reduction to zero takes place when \( d_o < 0.1 \mu m \) (Fig. 8). The value of \( v \) is

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**Table 2. Streaming potentials in NUCLEPORE membranes in equilibrium with 0.03 M KCl and NaCl solutions.**

<table>
<thead>
<tr>
<th>Pore diameter /( \mu m )</th>
<th>Streaming potential/10^{-2} ( \mu V , Pa^{-1} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( 0.015 )</td>
<td>( v_{KCl,0.03} )</td>
</tr>
<tr>
<td>( 0.05 )</td>
<td>2.2</td>
</tr>
<tr>
<td>( 0.1 )</td>
<td>1.9</td>
</tr>
<tr>
<td>( 0.2 )</td>
<td>2.3</td>
</tr>
<tr>
<td>( 0.4 )</td>
<td>2.0</td>
</tr>
<tr>
<td>( 0.6 )</td>
<td>1.9</td>
</tr>
<tr>
<td>( 1.0 )</td>
<td>1.8</td>
</tr>
</tbody>
</table>

---

**Fig. 4.** Typical variation of emf, \( E \), vs. time, \( t \), for a membrane with pore diameter 0.1 \( \mu m \) equilibrated in 0.001 M KCl. The \( \Delta p \) is given in cm H\(_2\)O on each curve.

**Fig. 5.** Maximum potential during several short (3–5 s) pressure pulses, for 0.03 M NaCl and \( d_o = 0.6 \mu m \).

**Fig. 6.** Emf as function of \( \Delta p \) for two membranes with \( d_o = 0.4 \mu m \) at long (■) and short (△) pressure pulses.

**Fig. 7.** Streaming potentials in 0.03 M KCl (■) and NaCl (△) as a function of membrane pore diameter.
Transference factors for dilute solutions of LiCl, NaCl and KCl

The results for the 0.001 M KCl solution indicate a transition zone around \( d_e = 0.2 \mu \text{m} \). According to equations (4) and (5) we expect a constant value beyond a certain radius \( r_s \), and a linear reduction to zero as \( r_s \) becomes \( \delta r \). According to this we may take \( r_s = 0.1 \mu \text{m} \) as an estimate for \( \delta r \) from Fig. 8. We apply equation (4) and obtain \( \delta r = 50 \text{nm} \). This means that also an estimate for the transference factor relative to the bulk can be obtained. According to equation (5) we have:

\[
\frac{dv_{2o}}{dr} = 2 \frac{dv_{1o}}{dr} = \frac{\tau}{4\eta} \quad \text{(6)}
\]

According to Fig. 8, the limiting slope of this equation is approximately 20 V Pa\(^{-1}\) m\(^{-1}\) for KCl. The solution viscosity is taken as that of water at 25°C, \( \eta = 10^{-3} \text{ Ns m}^{-2} \). This gives from equation (6) that \( \tau_{\text{KCl}} = 0.08 \text{ N A}^{-1} \) at the wall for \( c = 10^{-3} \text{ M} \) KCl. Thus from the flat part of the curves of Fig. 8, we can derived that \( \tau_{\text{KCl}} = 0.08 \), \( \tau_{\text{NaCl}} = 0.09 \) and \( \tau_{\text{LiCl}} = 0.11 \text{ N A}^{-1} \). These derivations cannot be performed for higher concentrations.

5. DISCUSSION

Time variations in emf

According to Figs 5 and 6, the value of the streaming potential at steady state may depend on the history of the sample. This means that membrane pretreatment is important for reproducible results. It is not enough to refer to steady state, the way the state is obtained may influence the result. Before use, the negative membrane surface charges are all compensated by the alkali metal ions in the equilibrating solution (say K\(^+\)). In the large pore, we may also have a layer of adsorbed salt, KCl. When the pressure pulse is applied for a too long period, or is applied too often, the equilibrium layer of KCl can be disturbed, and the character of the membrane-ion interaction is changed. We explain the results of Figs. 5 and 6 by such disturbances. The NUCLEPORE membrane is a weak acid, so the membrane may also exchange cations with protons. This may also affect the experimental result. Such effects are more likely (for the same \( \Delta p \)) in large pores than in small pores, because of increased fluid velocity in the former.

Irreversible transport processes superimposed on emf

Time dependent phenomena of the cell (ie diffusion and volume flow) will contribute to emf, but only indirectly. The surface layer disturbance discussed above for large pores is one such effect. Another effect which can be seen at low pore diameters is concentration polarization. The linear relation between \( E \) and \( \sqrt{t} \) in cation exchange membranes was explained by concentration polarization across the membrane[5]. The polarization was due to dilution of the salt concentration on the low pressure side and concentration of the salt on the high pressure side. The rate of the dilution, or the water permeability, was estimated from the slope of the curve. The results of Fig. 3 are taken as an indication of a similar phenomenon. The asymmetry in salt concentration then gives concentration cell contributions to the emf. The contribution is larger with NUCLEPORE membranes than with cation exchange membranes. This is expected, since the slope is a measure of the water permeability. The effect, when properly handled, does not affect the determination and reproducibility of \( \nu \), however.

Electrolyte effects

The direct cause of emf is the reversible split of solvent and salt constituent velocities at the wall, given by the particular membrane-solution interaction (see Ref. [5]). A high separation effect can be expected if the interaction between the membrane and the constituents of the salt is different from the interaction between the salt and the solvent (see "membrane effects" below).

In principle, the results in Fig. 8 have their origin in different salt velocities caused by the wall. A high streaming potential indicates that the ratio of salt velocity to solvent velocity is high, but it is not the decoupling of the salt velocity from the solvent velocity as such which causes the effect, rather it is the splitting of the cationic and anionic motions which leads to the observed streaming potential. The splitting of velocities occurs without charge accumulation, however, at the anode and cathode, chemical reactions corresponding to the constituent fluxes occur.

The form of: the streaming potential predicted by equations (2)–(4) was obtained for 0.001 M KCl and for 0.001 M NaCl and LiCl[2]. As we have shown, the results for the 0.03 M solutions did not reveal a similar dependency on \( r_s \). The results indicate that the quantity \( \delta r \) may play a role similar to the Debye
length, it characterizes the spatial extension of the salt molecule in solution. It decreases with increasing salt concentration. The value of $\delta r$ is of the same order of magnitude as the momentum producing layer extends of Fig. 8 (0.1 $\mu m$) and as the Debye length, which is 0.03 $\mu m$ in 0.001 M solutions. 

For the series of electrolytes we see that the greater the extension of $\delta r$ is into the liquid, the more space is available for the production of momentum, and the higher is the maximum value of the steaming potential. This observation is consistent with the qualitative prediction of equations (4) and (5).

For $r, > \delta r$ the variation of emf with time in the course of the experiment changes. This knowledge may be useful for further studies of $\delta r$ and $\tau$ as membrane-solution properties. So far we have used a non specific name for $\delta r$ (ie the transition layer or the interface layer). We propose that the term "electro-active layer" should be used for this layer which is active in momentum transfer between membrane and solution. The thickness of the layer expresses the extension of the chemically bound salt molecule in solution. Further studies of $\delta r$ and $\tau$ may modify tentative functions used so far, see equation (2). The estimates for $\delta r$ and $\tau$ in section 4 give a magnitude of the retardation/acceleration term in the equation of motion, equation (3).

According to Fig. 8, the maximum values follow the order $v_{KCl} < v_{NaCl} < v_{LiCl}$ for NUCLEPORE membranes. Khedr et al.[12] found the order $v_{CsCl} < v_{KCl} < v_{NaCl} < v_{LiCl}$ for cellulose acetate membrane. Scibona et al.[12] found the order $v_{OH^-} < v_{Na^+} < v_{LiOH}$ for Nafion 120. It seems that the streaming potential in porous materials increases with decreasing alkali cation radius, or increasing $\delta r$ and $\tau$ may modify tentative functions used so far, see equation (2). The estimates for $\delta r$ and $\tau$ in section 4 give a magnitude of the retardation/acceleration term in the equation of motion, equation (3).

Very low streaming potentials are observed with acid solutions[7]. The momentum distribution factor in equation (7) is then negative, but of markedly smaller magnitude than in the case of Li$^+$, and the proton binding to the negative groups in the wall is strong, causing a negative $v_{ex}$ of large magnitude. The relative velocity between HCl and solvent then becomes large. The effects taken together make a small $\tau$. When methanol is added to a LiCl solution, the streaming potential is reduced[4]. Methanol causes a strengthening of solvation of Li$^+$ and Cl$^-$ and influence all factors contained in equation (7), but obviously the interaction effect $v_{ex}$ dominates. Also for the 2-1 electrolyte solutions a decrease in the streaming potential with increasing cation radius is observed $v_{MgCl_2} > v_{CaCl_2} > v_{BaCl_2}$.[2, 15]. We expect that the cation-wall interaction is stronger for Mg$^{2+}$ than for Li$^+$. On the other hand, the larger molecular mass reduces the salt velocity of MgCl$_2$ more. So the result $v_{MgCl_2} \approx v_{LiCl}$ is understandable. Systematic investigations of these factors should be carried out.

In summary, we may say that we have a fair explanation for the salt-dependence on $\tau$. A quantitative prediction of the ratio $u/v_{ex}$ is lacking however.

Membrane effects

Most investigations report studies of one type of membrane. Investigations of different materials may reveal information on variations of $u/v_{ex}$ in equation (7) for constant solution properties. Material properties—concentration of charged groups at the pore wall, the chemical nature of the surface charge etc., must determine the ion-membrane interactions and therefore $v$. For instance, the high streaming potential observed with teflon pores can be understood by a high repulsion between water and the carbon fluoro network while maintaining some attraction to anions[14, 15]. The streaming potentials for cellulose acetate membranes are smaller than those for NUCLEPORE membranes. The cellulose acetate membranes have less well defined pores so that quantitative information on the pore radius dependency cannot be obtained.
CONCLUSIONS

This paper documents an experimental procedure to measure streaming potentials with 2% reproducibility for NUCLEPORE membranes with pore diameters < 0.05 μm, and with 5% reproducibility for diameters up to 0.4 μm. Increased uncertainties in the results for larger pore diameters are due to membrane multiple pores.

It appears that the electrokinetic behavior of the membrane can be classified according to the variation of emf with time when a pressure is applied to the cell.

The streaming potential variation with pore radius and concentration is in agreement with observations reported in the literature. The results can be described on a phenomenological level by a new electrokinetic theory, the electric work method, which does not use electric conductivity or electric charge separation as parameters but the difference in velocities for the salt constituents and the solvent velocity. The electric work method makes a new prediction on the streaming potential variation with pore radius: The connection between the limiting steepness as \( r_0 \rightarrow 0 \), and the maximum potential level. The electroactive layer, \( \delta r \), is important in this respect. It may modify the physical interpretation of the Debye length in the description of streaming potentials.

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