Effect of Finite Electric Double Layer Conductivity on Streaming Potential and Electroviscous Effect in Nanofluidic Transport

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ABSTRACT

In this paper, the role of finite Electric Double Layer (EDL) conductivity on the Streaming Potential and the resulting Electroviscous effect in pressure-driven nanofluidic ionic transport is investigated. Important dimensionless parameters like the Dukhin number (based on the EDL surface electrical conductivity, the bulk electrical conductivity and the EDL thickness), ratio of the Stern Layer and the Diffuse Layer conductivities and the ratio of the channel height to the EDL thickness are identified as important dimensionless parameters that dictate the contribution of the finite EDL conductivity. For most of the combinations of these dimensionless parameters, the finite EDL effect lowers the strength of the streaming potential and hence the electroviscous action. However, for certain choices of these parameters, particularly for moderate Dukhin number and substantially large zeta potential, finite EDL conductivity effect can actually enhance these effects.

1. INTRODUCTION

In the present decade, investigations on transport in nanofluidic confinements have received a tremendous boost, paving the way for a large number of novel chemical and biological applications in diverse areas such as biomedical, biotechnological, chemical, forensic etc [1-8]. Because of strong dominance of surface effects and interfacial phenomena over reduced length scales, flow manipulation through exploitation of electrical fields turns out to be convenient in nano-scale fluidic devices of practical relevance. Many such devices essentially function by exploiting the formation of electrical double layer (EDL) [9], which is essentially a charged layer formed in vicinity of the fluid-substrate interface because of electro-chemical phenomena. Under the action of driving forces, ionic charges in the mobile part of the EDL can migrate along a preferential direction, thereby giving rise to local ionic currents. The ionic transport in the EDL may also drag fluid elements along with the same as a consequence of viscous shear, which may bear significant consequences with regard to the hydrodynamic transport in the narrow confinement. Critical to the investigation of electrokinetic transport, thus, lies the analysis of hydrodynamics within the EDL.

Advection of mobile ions present within the EDL, in presence of a pressure-driven background flow, develops a so called streaming potential [9] in micro and nanochannels. Streaming potential is effectively the induced electric field created due to a preferential downstream accumulation of the EDL.
counterions and is directed opposite to the pressure-driven transport. Consequently, it sets up a back electrokinetic transport which opposes the pressure-driven flow. The resulting reduction in the volume flow rate makes the flow appear to have an enhanced viscosity, an artifact known as Electroviscous Effect. Researchers have utilized the generation of streaming potential for a number of applications which include the conversion of hydrostatic pressure differences into useful electrical energy, characterization of interfacial charge of organic thin films, measurement of wall charge inversion in the presence of multivalent ions in a nanochannel, analysis of ion transport through nanoporous membranes, designing efficient nano-fluidic batteries, quantifying hydrodynamic dispersion in nanochannels, etc.

Streaming potential is estimated by balancing the streaming current (current resulting from flow induced downstream migration of mobile EDL ions) with the conduction current (current resulting from the streaming potential induced reverse electro-migration of ions), under steady state condition. A precise determination of the conduction current, in turn, depends on an accurate quantification of the conductivity of the ionic solution. The standard practice is to characterize the conductivity by a unique value dictated by the bulk ionic concentration. This approach works fine for microchannels where the EDL occupies only a negligible extent of the channel section. However, for nanochannels in which EDLs may protrude significantly into the bulk, this approach may not turn out to be quite adequate. This inadequacy stems from the fact that within the EDL the concentration of ions can be much higher so that the corresponding value of the conductivity is much larger than the bulk conductivity. In fact, within the EDL itself, large differences in the ionic concentration between the immobile Stern layer and the mobile diffuse layer may result in different conductivities at different sections of the EDL. A correct estimation of conduction current (and hence streaming potential and electroviscous effect estimation) in nanofluidic transport must take into account these variable conductivities across different portions of the channel section. There has been a large number of investigations delineating the effects of finite EDL conductivity (or to be more specific, Stern Layer conductivity) on different aspects of electrokinetic transport [10-16]. However, to the best of our knowledge, there has been no investigation pinpointing the influences of the differences in EDL and bulk conductivities on nanochannel streaming field and electroviscous effect calculations. Only very recently, Davidson and Xuan [17] elaborated the effects of Stern layer conductance on electrokinetic energy conversion in nanochannels. However, in their work they did not consider the effect of the diffuse layer, neither they pinpointed the possible variations of the streaming potential and the effective viscosity (characterizing the electroviscous effect) as a function of the different parameters governing the finite conductivity within the EDL.

In the present paper we pinpoint the possible effects of considering finite EDL electrical conductivities (different from the bulk value) in altering the streaming potentials and the resulting electroviscous action. The EDL itself is assumed to have two different conductivities; one for the Stern Layer and another for the Diffuse Layer. Based on the combination of these conductivities with the bulk conductivity, along with the value of the EDL thickness, we identify the relevant dimensionless parameters that govern the extent of deviation of the streaming potential for the cases with and without the considerations of varying electrical conductivities over the channel section.

2. THEORY

2.1 EDL potential and Streaming Field without Considering Finite EDL Conductivity

We consider transport of an ionic liquid in a slit-like charged nanochannel of height $2H$, length $L$ and width $w$. The EDL potential field ($\psi$) in the nanochannel is described in terms of the net charge density ($\rho_e$) within the EDL as:

$$\frac{\partial^2 \psi}{\partial x^2} + \frac{\partial^2 \psi}{\partial y^2} = -\frac{\rho_e}{\varepsilon_0 \varepsilon_r}$$

where $\varepsilon_0$ is the permittivity of free space and $\varepsilon_r$ is the relative permittivity of the solution. The charge density $\rho_e$ is expressed in terms of the ionic number densities for symmetric electrolyte ($z_+ = -z_- = z$) as:

$$\rho_e = \varepsilon_0 \varepsilon_r (n_+ - n_-)$$
Assuming that the ionic concentrations obey Boltzmann distributions \( n_\pm = n_0 \exp \left( \pm \frac{e_{\pm} \psi}{k_B T} \right) \)

where \( n_0 \) is the bulk ionic concentration, eqs. (1) and (2) are solved to obtain the solution of the potential field (under the condition that at \( \psi \rvert_{y=0,2H} = \zeta \) (zeta potential) and \( \frac{d\psi}{dy} \rvert_{y=H} = 0 \)

and the EDL thickness \( \lambda \) is comparable but always less than the channel half height) as [9]:

\[
\psi = -\frac{4k_T}{ze} \left[ \tanh^{-1} \left( \frac{e_{\pm} \zeta}{4k_BT} \exp \left( -\frac{y}{\lambda} \right) \right) \right]
\]

(3)

In presence of a pure pressure-driven transport downstream migration of the mobile EDL ions give rise to what is known as the streaming current. The resulting accumulation of the ions in the downstream establishes a field (called the streaming field or streaming potential) in the upstream direction which drives a current called the conduction current. The net ionic current is a resultant of these two effects and at steady state is equal to zero. We thus have:

\[
I_{\text{ionic}} = I_{\text{str}} + I_{\text{cond}} = 0
\]

(4)

The streaming current \( I_{\text{str}} \) is expressed as:

\[
I_{\text{str}} = \int_0^{2H} \rho_\text{str} u dy = e \int_0^{2H} (n_+ - n_-) u dy
\]

(5)

Following the argument proposed in our previous work [18], the velocity field, \( u \), as appearing in Eq. (5), needs to be considered as a resultant of the imposed pressure-driven transport and the opposing streaming field induced electroosmotic transport, such that:

\[
u = \nu_p + \nu_{E_S} = -\frac{1}{2\mu} \frac{dp}{dx} (2Hy - y^2) \left( \frac{e_{\pm} \psi}{k_B T} \right) \frac{\exp \left( \frac{e_{\pm} \psi}{k_B T} \right)}{\zeta} \left( 1 - \frac{\psi}{\zeta} \right)
\]

(6)

\[
I_{\text{cond}} = e \int_0^{2H} \left( n_+ u_{\text{cond},+} + n_- u_{\text{cond},-} \right) dy
\]

(7)

where \( u_{\text{cond},\pm} \) are the electromigration velocities of the cations/anions in response to the streaming potential, and may be expressed as

\[
u_{\text{cond},\pm} = \frac{zeE_S}{f_{\pm}}
\]

(8)

Here \( f_{\pm} \) are the friction coefficients of the ions, which is assumed to have identical values for the anions and the cations (i.e., \( f_+ = f_- = 6\pi\mu r_{\text{ion}} \)), where \( r_{\text{ion}} \) is the ionic radius; here we assume, with some degree of approximation, that the cationic and anionic radii are approximately equal to around 1.5 A°, leading to (using eqs. 7 and 8)

\[
I_{\text{cond}} = e \int_0^{2H} \left( n_+ \nu_+ + n_- \nu_- \right) dy
\]

(9)

Using Boltzmann distribution to express the ionic concentrations (i.e., \( n_\pm = n_0 \exp \left( \pm \frac{e_{\pm} \psi}{k_B T} \right) \)), we rewrite eq. (9) as:

\[
I_{\text{cond}} = \frac{e^2 E_S}{f} \int_0^{2H} \left( n_+ + n_- \right) dy
\]

(10)

where \( \frac{dp}{dx} \) is the pressure gradient, \( \mu \) is the dynamic viscosity of the fluid and \( E_S \) is the induced streaming potential field.

The conduction current \( I_{\text{cond}} \) results from the transport of the ions in response to the established streaming potential, so that one may write (assuming that the ions have identical conduction velocities across the entire transverse domain, i.e., the variation of the mobilities of the ions depending on whether they are in the bulk or within the EDL is not accounted for)

\[
I_{\text{cond}} = e \int_0^{2H} \left( n_+ u_{\text{cond},+} + n_- u_{\text{cond},-} \right) dy
\]

(7)

where \( u_{\text{cond},\pm} \) are the electromigration velocities of the cations/anions in response to the streaming potential, and may be expressed as

\[
u_{\text{cond},\pm} = \frac{zeE_S}{f_{\pm}}
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Here \( f_{\pm} \) are the friction coefficients of the ions, which is assumed to have identical values for the anions and the cations (i.e., \( f_+ = f_- = 6\pi\mu r_{\text{ion}} \)), where \( r_{\text{ion}} \) is the ionic radius; here we assume, with some degree of approximation, that the cationic and anionic radii are approximately equal to around 1.5 A°, leading to (using eqs. 7 and 8)

\[
I_{\text{cond}} = e \int_0^{2H} \left( n_+ \nu_+ + n_- \nu_- \right) dy
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Using Boltzmann distribution to express the ionic concentrations (i.e., \( n_\pm = n_0 \exp \left( \pm \frac{e_{\pm} \psi}{k_B T} \right) \)), we rewrite eq. (9) as:

\[
I_{\text{cond}} = \frac{e^2 E_S}{f} \int_0^{2H} \left( n_+ + n_- \right) dy
\]

(9)

Using eqs. (4), (5), (6) and (9) we finally obtain:
2.2 Streaming Field Considering Finite EDL Conductivity

Consideration of finite conductivity within the EDL, or in other words, considering different ionic mobilities in the bulk and the EDL leads to alteration in the expression of the conduction current, although the streaming current remains unchanged. The modified expression for the conduction current now reads:

\[
E_{\text{cond}} = \frac{\sigma_s E_S + \sigma_{\text{Diff}} E_S}{\lambda - 2 \eta_{0}} \int_{2H}^{\lambda} \cosh \left( \frac{e \psi}{k_B T} \right) dy + \int_{2H-\lambda}^{2H} \cosh \left( \frac{e \psi}{k_B T} \right) dy
\]

(11)

In eq. (12), the first two terms on RHS represent the conduction current within the Stern and Diffuse Layer and the last term accounts for the conduction current outside the EDL. Using eq. (12), along with eqs. (4), (5) and (6), we obtain the modified expression for the streaming field \( E'_{S} \), accounting for the finite EDL conductivity, as:

\[
E'_{S} = \frac{n_{0} e \int_{0}^{2H} \left[ - \frac{1}{2} \frac{dp}{dx} (2H - y^{2}) \right] \sinh \left( \frac{e \psi}{k_B T} \right) dy}{\frac{\eta_{0}}{2} \left[ \frac{1}{\mu} \frac{dp}{dx} (2H - y^{2}) \right] \int_{0}^{2H} \cosh \left( \frac{e \psi}{k_B T} \right) dy + \int_{2H}^{\lambda} \cosh \left( \frac{e \psi}{k_B T} \right) dy + \int_{2H-\lambda}^{2H} \cosh \left( \frac{e \psi}{k_B T} \right) dy + \frac{n_{0} e \psi_{0} e_{0} e_{S}}{\mu} \int_{0}^{2H} \left[ 1 - \frac{\psi}{\zeta} \right] \sinh \left( \frac{e \psi}{k_B T} \right) dy}
\]

(13)

Using this expression, we obtain the ratio of the streaming field for the two cases (in terms of different dimensionless parameters and variables as:)

\[
\frac{E'_{S}}{E_{S}} = \frac{\int_{0}^{\lambda} \cosh \left( \frac{4 \psi}{\zeta} \right) d\psi + R_{D} \int_{0}^{\lambda} \left[ 1 - \frac{\psi}{\zeta} \right] \sinh \left( \frac{4 \psi}{\zeta} \right) d\psi}{\int_{0}^{\lambda} \cosh \left( \frac{4 \psi}{\zeta} \right) d\psi + \frac{2 \eta_{0}}{2} + \int_{2H}^{\lambda} \cosh \left( \frac{4 \psi}{\zeta} \right) d\psi + \int_{2H-\lambda}^{2H} \cosh \left( \frac{4 \psi}{\zeta} \right) d\psi + \int_{2H-\lambda}^{2H} \cosh \left( \frac{4 \psi}{\zeta} \right) d\psi}
\]

(14)

where the different dimensionless variables and parameters are:

\[ \tilde{y} = y / H, \quad \tilde{\psi} = e \psi / 4k_{B}T, \quad \zeta = e\psi / 4k_{B}T, \]

\[ R_{i} = \frac{8n_{0} e_{0} e_{S} k_{B} T}{\mu \sigma_{b}} \] (equivalent to ionic Peclet number, as described in our previous work [18]),

\[ D_{u} = \frac{\sigma_{s} + \sigma_{\text{Diff}}}{\sigma_{s} \lambda} \] (Dukhin number denoting the ratio of the EDL surface conductivity and the bulk conductivity) and \( K_{e} = \sigma_{s} / \sigma_{\text{Diff}} \) (ratio of the Stern Layer and Diffuse Layer conductivities).

2.3 Electroviscous Considerations: Effects of EDL Conductivity

Electroviscous effect is accounted for by calculating the enhanced viscosity obtained by balancing the volume flow rate for pure pressure-driven transport (with enhanced viscosity) with combined pressure-driven and streaming field induced back electroosmotic transport (with original viscosity). Thus the effective viscosity for the cases without and with finite EDL conductivity effect is calculated as:

\[
\mu_{eff} = \frac{1}{\int_{0}^{2H} \frac{dp}{dx} / \mu} \frac{\int_{0}^{2H} \frac{dp}{dx} (2H - y^{2}) \int_{0}^{2H} \left[ 1 - \frac{\psi}{\zeta} \right] dy}{1 / \mu - \frac{\int_{0}^{2H} \frac{dp}{dx} (2H - y^{2}) \int_{0}^{2H} \left[ 1 - \frac{\psi}{\zeta} \right] dy}{\frac{1}{\mu} - \frac{\int_{0}^{2H} \frac{dp}{dx} (2H - y^{2}) \int_{0}^{2H} \left[ 1 - \frac{\psi}{\zeta} \right] dy}}
\]

(15)

(without considering EDL conductivity)
\[
\mu'_{\text{eff}} = \frac{dp}{\mu} \left( \frac{2H^3}{3} + \frac{\zeta \mu}{\mu} \int_0^1 \left( 1 - \frac{\psi}{\zeta} \right) d\psi \right)
\]  
(considering EDL conductivity)

Consequently the ratio of these effective viscosities is calculated as:

\[
\frac{\mu'_{\text{eff}}}{\mu_{\text{eff}}} = 1 + \frac{\int_0^1 \left( 1 - \frac{\psi}{\zeta} \right) d\psi}{\int_0^1 \left( 1 - \frac{\psi}{\zeta} \right) d\psi} = 1 + \frac{2}{4} K_U \left( 1 - \frac{\psi}{\zeta} \right) d\psi
\]

where \( K_U = \frac{(u_{e1})_{\text{max}}}{(u_p)_{\text{max}}} \) is the ratio of the maximum electroosmotic (streaming field (without considering finite EDL conductivity) induced) velocity to the maximum pressure-driven velocity and \( K'_{U} = \frac{(u_{e1})_{\text{max}}}{(u_p)_{\text{max}}} \) is the ratio of the maximum electroosmotic (streaming field (considering finite EDL conductivity) induced) velocity to the maximum pressure-driven velocity.

### 3. RESULTS AND DISCUSSIONS

We perform the simulations with the following values of the system parameters:

\( H = 50 \text{ nm}, \mu = 0.001 \text{ Pa-s}, \varepsilon_r = 79.8, T = 300 \text{ K} \).

Figure 1 depicts the variation of \( E_{S}' / E_S \) with dimensionless zeta potential for different combinations of \( D_u, K_r \) and \( H/\lambda \). In inset of the figure we plot the effective conductivities \( (\sigma_{\text{eff}}) \) having units of S, for the cases with and without the EDL conductivity. With EDL effect, it is

\[
\sigma_{\text{eff}} = 2\sigma_S + \frac{\sigma_{\text{Diff}}}{(\lambda - 2\chi_{\text{ion}})} \left[ \int_0^{2H} \cosh \left( \frac{e\psi}{k_B T} \right) d\psi + \int_{2H - \chi_{\text{ion}}}^{2H} \cosh \left( \frac{e\psi}{k_B T} \right) d\psi \right]
\]

whereas without EDL conductivity it is expressed as

\[
\sigma_{\text{eff}} = \sigma_S \int_0^{2H} \cosh \left( \frac{e\psi}{k_B T} \right) d\psi
\]

The difference between \( E_S \) and \( E_S' \) originates from the differences in conduction current resulting from the consideration of finite EDL conductivities, much different from the bulk conductivity. As zeta potential increases, the strength of the streaming field induced back electroosmosis (an effect introduced in our previous study [18]) rapidly increases outweighing the corresponding increase in the contribution of the conduction current. These two effects simultaneously balance the component of the streaming current caused by the pressure-driven downstream advection of mobile counterions. Consequently at larger zeta potential, the influence of the conduction current is lessened, lowering the differences between \( E_S \) and \( E_S' \). Larger the value of \( H/\lambda \) greater is the strength of the streaming field induced back electroosmosis, thereby resulting in an even smaller difference between \( E_S \) and \( E_S' \). When \( Du \) number is large, the Stern Layer and Diffuse Layer conductivities become much larger than the bulk conductivity so that the difference between \( E_S \) and \( E_S' \), for a given \( H/\lambda \) and \( K_r \), is enhanced, leading to a smaller value of the \( E_S' / E_S \) ratio.
A very important result of this study is the effect of $K_r$ on the ratio $E_s' / E_s$. Dependence of this ratio on $K_r$ reflects the relative contribution of the Diffuse Layer and the Stern Layer conductivities on dictating the strength of the streaming field. The Stern Layer effect is manifested simply through the value of the Stern Layer conductivity ($\sigma_{St}$). On contrary, the Diffuse Layer effect is reflected through the effective Diffuse Layer conductivity

\[
\sigma_{Diff} = \frac{\sigma_{Diff}}{\lambda - 2\text{f}_{\text{ion}}}
\]

which is thus a function of the zeta potential (i.e., higher the zeta potential larger is its contribution) also. Consideration of this effective value ensures that the contribution of the Diffuse Layer effect can be comparable or be even more than the Stern Layer effect, although the ratio $K_r = \frac{\sigma_{St}}{\sigma_{Diff}}$ is much greater than unity. The result is that for relatively smaller values of $K_r$ ($K_r = 3, 5$, for instance), the contribution of the overall EDL conductivity is enhanced, leading to a much smaller value of the ratio $E_s' / E_s$. At larger zeta potential, the influence of the effective Diffuse Layer conductivity, and hence the effect of the net EDL conductivity, is enhanced leading to the maximum weakening of $E_s'$ relative to $E_s$.

The most interesting aspect of Figure 1 is the possibility of the ratio $E_s' / E_s$ becoming more than unity for relatively small values of $Du$ and small values of $H/\lambda$, at very large zeta potential values. To explain such behaviour we show the variation of the effective conductivities with dimensionless zeta potential, for the cases with and without the finite EDL effect (See inset of Figure 1). It is found that for extremely large values of the zeta potential, the effective conductivity for the case without considering separate EDL conductivity actually outweighs that of the case with EDL effect. Consequently the ratio $E_s' / E_s$ shows a value larger than one. For the cases in which $E_s' / E_s$ approaches unity for large $Du$ (i.e., small enough $H/\lambda$ or small enough $K_r$), the ratio $E_s' / E_s$ is further enhanced beyond 1 (for small enough $Du$).

Figure 2 gives the variation of the ratio viscosity ratio $\left(\frac{\mu_{eff}}{\mu_{eff}}\right)$ with dimensionless zeta potential (ez$\zeta$/4$k_B$T)) for different combinations of the relevant dimensionless parameters. Contrary to the trends in the variations of the $E_s' / E_s$ ratio, $\frac{\mu_{eff}}{\mu_{eff}}$ ratio does not show a monotonic variation with the dimensionless zeta potential. The functional form of the $\frac{\mu_{eff}}{\mu_{eff}}$ ratio ensures that it depends more on the individual variations in the streaming field values for the two cases (with and without considering the EDL conductivity), rather than the ratio $E_s' / E_s$. Consequently the zeta potential dependence of this ratio follows a qualitative variation, commensurate with the variation of the individual streaming field values (in the inset of figure 2 we show the variation of $E_s'$ and $E_s$ with dimensionless zeta potential, for a given combination of values of dimensionless parameters). For small enough zeta potentials (where $E_s$ is always larger than $E_s'$), $E_s$ rapidly decreases with zeta potential. Similar qualitative decrements (though to a much lesser extent) are noted for the case of $E_s'$. Thus, one may expect that over such zeta potential ranges, there is likely to be a decrease of the ratio $\frac{\mu_{eff}}{\mu_{eff}}$ with increments in zeta potential.

![Figure 2: Variation of viscosity ratio ($\frac{\mu_{eff}}{\mu_{eff}}$) with dimensionless zeta potential (ez$\zeta$/4$k_B$T)) for different combinations of $Du$, $H/\lambda$, and $K_r$. In the inset of the figure, we plot the variation of $E_s$ and $E_s'$ with dimensionless zeta potential for some of these combinations of $Du$, $H/\lambda$, and $K_r$.](image-url)

Both $E_s$ and $E_s'$ reach a maximum value at an intermediate zeta (this zeta value may be...
different for $E_s$ and $E'_s$), beyond which both of these parameters decrease with increasing zeta potential. The consequence is that the difference between $E_s$ and $E'_s$ decreases (thereby decreasing the differences in their electroviscous influences), making the ratio $\frac{\mu_{\text{eff}}}{\mu_{\text{eff}}}$ increase (and approach a value closer to 1) with increments in the zeta potential. In fact, for certain combinations of the dimensionless parameters and at very large zeta potential values, $E'_s$ may become greater than $E_s$ (as seen in figure 1), resulting in a $\frac{\mu_{\text{eff}}}{\mu_{\text{eff}}}$ value greater than 1. Increase in $\frac{H}{\lambda}$ values decreases the difference between $E_s$ and $E'_s$, thereby resulting in a larger $\frac{\mu_{\text{eff}}}{\mu_{\text{eff}}}$ value (i.e., a value closer to 1) corresponding to a given value of the dimensionless zeta potential. With lowering of $K_r$ values, difference between $E_s$ and $E'_s$ gets enhanced, enforcing a lowering of $\frac{\mu_{\text{eff}}}{\mu_{\text{eff}}}$ for a given value of the dimensionless zeta potential. Finally, a decrease in $Du$ greatly decreases the difference between $E_s$ and $E'_s$, and can even make $E'_s$ exceed $E_s$. $\frac{\mu_{\text{eff}}}{\mu_{\text{eff}}}$ variation commensurate with such $E_s$ and $E'_s$ variation is seen in figure 2.

In nanoconfinements, the strength of the pressure-driven flow is substantially reduced by the presence of large streaming field and the resulting back electroosmotic transport. In this paper, it is illustrated that consideration of conductivity gradient across the different layers of the EDL and the bulk result in a weaker strength of the streaming field. This will mean that the flow strength can be significantly augmented by choosing suitable system parameters like the wall zeta potential, bulk ionic concentration, surface with desirable adsorptivity for the counterions, size of the counterions (these parameters dictate the conductivities of the Stern Layer and the Diffuse Layer and consequently the values of the Dukhin number and the ratio $K_r$). Hence by tailoring the Stern Layer and the Diffuse Layer conductivities by modifying the different physical parameters we can obtain desired nanofluidic flow behaviour.

4. CONCLUSIONS
The present study delineates the significant influences of finite EDL conductivities (significantly different from that dictated by bulk ionic concentrations) on the streaming potential and the resulting electroviscous effects in nanofluidic ionic transport. Even within the EDL, there can be significant differences in conductivities (depending on whether the region of interest is the wall-adjacent monoionic thick Stern Layer or the outer Diffuse Layer), which in turn can bear significant consequences on the streaming potential and effective viscosity predictions. The magnitude of the combination of these conductivity values in the two layers of the EDL relative to the bulk value of the solution conductivity (parameterized by the Dukhin number), in addition to the relative thickness of the EDL with respect to the channel height, dictate the eventual trends in the streaming potential and electroviscous effects as attributed to the EDL conductivity variations. When the Dukhin number is significantly large (indicating large values of EDL conductivity) or the value of $H/\lambda$ is sufficiently large, the streaming potential and the electroviscous effects for the case with varying conductivity effects within the EDL get significantly reduced, particularly for relatively small values of the zeta potential. On the contrary, however, for moderate Dukhin numbers and for very large zeta potentials, streaming potentials and the electroviscous effects may get significantly augmented and can actually exceed those obtained without variable EDL conductivity effects.

REFERENCES


