

## INDUCED CHARGE ELECTRO-OSMOSIS: THEORY AND MICROFLUIDIC APPLICATIONS

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*Summary* Induced-charge electro-osmosis (ICEO) involves the nonlinear electro-osmotic slip flow caused by an applied field acting on ionic charge *induced* around a conducting body or surface, wherein a rectification allows steady microfluidic flows to be driven using AC fields. Breaking the symmetry of the surface or field allows steady flows to be driven parallel or perpendicular to the applied AC field, suggesting a number of devices and strategies for microfluidic mixing, pumping, and manipulation.

### INTRODUCTION

Electrokinetic techniques are one of the most popular of non-mechanical fluid manipulation strategies for microfluidic flows (e.g. [1]). This popularity stems in part from the fact that many microfluidic applications naturally integrate electronic circuits for electrophoretic separations. Electro-osmotic flows are further favored in that they allow dispersionless plug flows (as opposed to parabolic pressure-driven flow) and because the large surface/volume ratios of microchannels suggest surface-driven flows. However, electro-osmosis has drawbacks: they depend sensitively on solution pH, salt concentration, and surface charge densities, and electrochemical (Faradaic) reactions are required to maintain a constant electric field, which introduces bubbles, metallic ions, and concentration gradients. Furthermore, high voltages are required to apply appreciable fields over significant distances.

In traditional electro-osmosis, an applied field acts upon the diffuse cloud of counter-ions surrounding a charged surface. The resulting body force drives the fluid into motion, resulting in Smoluchowski's 'slip velocity'

$$u_{\text{EOF}} = \frac{\epsilon_w \zeta E}{\mu}, \quad (1)$$

where  $\epsilon_w$  and  $\mu$  are the permittivity and viscosity of water,  $E$  is the applied field, and  $\zeta$  is the potential drop across the double-layer (proportional to surface charge density for small  $\zeta$ ). Clearly, a periodic applied field  $E(t)$  gives no time-averaged electro-osmotic flow.

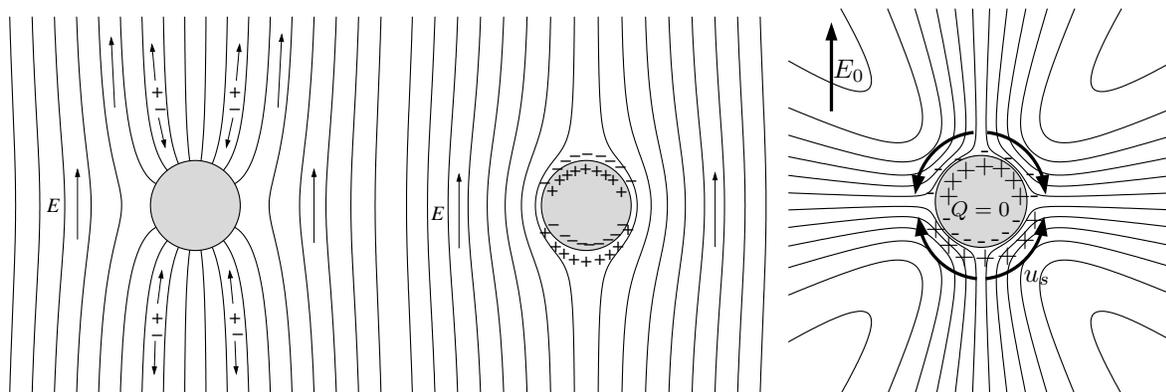
Recently, AC electrokinetic techniques have been introduced which overcome many of the drawbacks inherent in traditional electro-osmotic flow. In AC electro-osmosis, a time-varying applied field acts upon the transient charge cloud it *induces*. Since the applied field and the induced charge cloud both exhibit the same time-dependence, the resulting nonlinear electro-osmotic slip velocity has a non-zero, rectified component. Such phenomena have been exploited in colloidal self-assembly near electrodes [2, 3], driving counter-rotating fluid rolls above planar electrodes [4], and (by breaking spatial symmetry) to create microfluidic pumps [5, 6].

Such techniques involve transient charge clouds induced around the working electrodes, and thus work in a limited frequency range: they do not work at extremely high frequencies (where charge clouds do not have time to form), nor do they work at low frequencies (where the charge cloud completely screens the electrode, leaving no applied field). They do, however, avoid electrochemical reactions and are relatively insensitive to solution properties.

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Nonlinear electrokinetic phenomena, however, have a wider range of validity than AC electro-osmosis implies. Because the key physical ingredients involve electro-osmotic flows due to charge clouds *induced* by the applied field, we prefer the more general term 'induced-charge electro-osmosis' (ICEO) for their description. Fig. 1 presents the most basic picture of ICEO, which represents perhaps the simplest and cleanest example of a nonlinear electrokinetic phenomenon. In what follows, we discuss the scaling and relevant time scales for ICEO flows (under DC or AC fields), as well as microfluidic devices which employ them.

The basic phenomenon of ICEO is illustrated in Fig. 1, where a conducting cylinder is immersed in an electrolytic fluid. Immediately after an external field is applied, an electric field is set up that intersects the conductor at right angles (Fig. 1a). If the conductor were in vacuum, this would represent the steady-state field configuration. Mobile ions in solution, however, move in response to the applied field, and a current  $\mathbf{J} = \sigma \mathbf{E}$  drives positive ions into a charge cloud on one side of the conductor, and negative ions to the other. An equal but opposite charge is induced on the conducting surface to maintain the equipotential surface. A dipolar charge cloud grows until no field lines penetrate the double-layer in steady state (Fig. 1b). In steady state, the tangential field  $E_{\parallel}$  drives an electro-osmotic slip velocity (1) proportional to the local double-layer charge density, driving fluid



**Figure 1.** Induced-charge electro-osmosis. (a) Just after a DC field is applied, field lines intersect an ideally polarizable metal cylinder at right angles. Bulk currents charge a dipolar charge cloud over a charging time  $\tau_c = \lambda_D a/D$ , reaching steady state (b) when no field penetrates the double layer. The resulting zeta potential, however, is nonuniform, giving a quadrupolar ICEO flow (c).

from the ‘poles’ of the particle towards the ‘equator’ (Fig. 1c). Note that an AC applied field gives the same flow, since an oppositely-directed field induces an oppositely-charged screening cloud, and the net flow (which depends on the product of the field and the charge) is unchanged.

Simple pictures give the scaling of ICEO flows: locally, the electrokinetic slip velocity obeys (1), except that the local  $\zeta$  is now given by the difference between the potential of the conductor and the potential ‘outside’ the double-layer. For a cylinder of radius  $a$ , the induced  $\zeta$  has magnitude  $Ea$ , and the ICEO slip velocity has magnitude  $U_{\text{ICEO}} \sim \epsilon_w E^2 a / \mu$ . The time scale on which induced double layers form is given  $\tau_c = \lambda_D a / D$ , where  $D$  is the ionic diffusivity. This time scale, in an equivalent form, was also found in the context of AC electro-osmosis, where  $\tau_c^{-1}$  is roughly the frequency for optimal response [7]. The ICEO flow shown in Fig. 1c, however, can be driven by any field with sufficiently small frequency  $\omega < \tau_c^{-1}$ , even DC fields.

The analogous colloidal picture was originally explored in the Russian literature (see [8] and references therein.) We are interested in ICEO from a microfluidic standpoint, where additional degrees of freedom arise that are unavailable in colloidal systems. For example, in microfluidic devices, the potential of the ‘working conductor’ can be actively controlled, e.g. by grounding it to one of the driving electrodes. In this case of ‘fixed-potential’ ICEO, an additional rectification arises that causes a net, *directed* fluid flow.

The above examples have been highly symmetric. Breaking spatial symmetries often results in additionally rich physical phenomena, as shown by Ajdari [5]. Breaking the symmetry of the conducting cylinder in any of a number of ways causes a *directed* flow along the axis of broken symmetry, so that a steady flow can be driven either parallel or perpendicular to an AC applied field. Microfluidic pumps based on this effect are promising for several reasons: stronger flows can be driven using arrays of asymmetric posts distributed along a channel. Furthermore, strong flows can be driven with a small AC potential applied *across* the channel, using asymmetric posts to drive flows *along* the channel. Finally, asymmetric conducting colloids experience a directed electrophoretic motion under AC fields, and, e.g., objects can be designed that rotate under AC fields.

## CONCLUSION

In summary, induced-charge electro-osmosis is a potentially useful new technique for driving microfluidic flows. Low applied voltages are required, and a strong flow results that is insensitive to solution chemistry. We have presented a simple but general physical picture and touched upon the rich variety of ICEO phenomena, and thus we suggest ICEO as a promising new tool for the microfluidic toolbox.

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