Microfluid Nanofluid (2007) 3:709–714
DOI 10.1007/s10404-007-0168-1

SHORT COMMUNICATION

Novel systems for configurable AC electroosmotic pumping

Neophytos Loucaides · Antonio Ramos · George E. Georghiou

Received: 13 December 2006 / Accepted: 5 March 2007 / Published online: 5 April 2007

Abstract In this paper we present a novel method of creating and using geometric asymmetries for AC electroosmotic pumping. The method relies on grouping similar electrodes together in terms of applied voltage, in order to create configurable asymmetries in periodic electrode arrays, which induce a net pumping AC electroosmotic velocity. Using a numerical model for a system designed by applying the described method, it is demonstrated that by varying the degree of asymmetry it is possible to control the direction of the pumping velocity at a given voltage by simple switching of the voltages on the electrodes.

1 Introduction

Since the discovery of AC electroosmotic flows (Ramos et al. 1998, 1999), many methods have been proposed to utilize these in the pumping of fluids in capillaries, due to several advantages over DC electroosmosis. The main advantage is that the use of low AC voltage can reduce or eliminate Faradaic currents, which reduces or eliminates the generation of bubbles and new species in the liquid.

An important set of pumping systems that have been proposed and demonstrated, are ones that utilise asymmetries in the electric field, created by planar electrode structures in capillaries to produce a directional AC electroosmotic net flow of fluid (Ajdari 2000). In particular, a method utilising an asymmetry in the electrode geometric configuration has been demonstrated experimentally by Brown et al. (2001) and analyzed theoretically in Ramos et al. (2003), which describes the asymmetric array and predicts the right direction of the fluid flow. This electrode structure has also been utilized in the trapping of DNA using AC electroosmosis (Bown and Meinhart 2006). Another important set of pumping methods has been described in the literature that utilize travelling wave electric fields generated by symmetric electrode arrays for the purpose of fluid pumping (Cahill et al. 2004; Ramos et al. 2005). Asymmetries in this type of pumping systems can be introduced in many ways, such as asymmetries in the shape of the electrodes (Brown et al. 2001) or their properties (Ajdari 2000) or even by adding DC bias in the electrode excitation (Wu et al. 2005; Wu 2006). Proposed methods also include three-dimensional asymmetric electrode structures (Urbanski et al. 2006; Bazant and Ben 2006). Generalizations of AC electroosmosis are also under investigation, such as Induced Charge Electroosmosis (Bazant and Squires 2004).

An interesting issue in AC electroosmotic pumping using asymmetric electrode arrays is the reversal of the pumping direction. For low voltages and frequencies, the expected flow occurs at the side of the smaller electrode towards the larger one. This flow has been shown to reverse at higher voltages and frequencies (Studer et al. 2004; Garcia-Sanchez et al. 2006). However, the mechanism that causes flow reversal is yet unclear (although Faradaic currents have been proposed as an explanation for this) (Ajdari 2000; Lastochkin et al. 2004). Possible undesirable effects on the electrodes have also been associated with high voltages, such as the formation of bubbles due to

N. Loucaides (✉) · G. E. Georghiou
Department of Electrical and Computer Engineering,
University of Cyprus, Nicosia, Cyprus
e-mail: eep4nl1@ucy.ac.cy

A. Ramos
Department of Electronics and Electromagnetism,
University of Seville, Seville, Spain

electrolysis and the degradation of the electrodes (Garcia-Sanchez et al. 2006). Recently, there has been an investigation into the effect of Faradaic currents, as well as other important factors on AC electroosmotic flow (Olesen et al. 2006), such as vertical confinement and nonlinear surface capacitance.

This paper proposes a method of creating configurable geometric asymmetries in a system of arrays of identical electrodes, as shown in Fig. 1 (system B) and Fig. 2. The system operates by applying the same AC voltage on two adjacent electrodes (say 1 and 2) while applying a voltage of equal magnitude in anti-phase to the other electrode (therefore the system consists of triplets of identical electrodes instead of pairs of non-similar electrodes, with another possibility being an arbitrarily wide middle electrode with identical electrodes at the two sides). This can also be implemented by applying a single AC signal to one electrode group while earthing the other. A geometric asymmetry similar to the one in a system of asymmetric electrodes is created, as described in Studer et al. (2004) and shown in Fig. 1 (system A), with the significant advantage that in the proposed system this asymmetry is configurable, as shown in Fig. 1 (system B).

The proposed method may be used to create configurable asymmetry by employing a number of identical electrodes and therefore can be used to control the direction of the pumping velocity, without the need for high applied voltage. It is also demonstrated here that the amplitude of the pumping velocity can be controlled in a step-wise manner depending on the number of electrodes in a group.

Finally, it is worth noting that the proposed system allows for flow reversal at any voltage (both low and high) without the need to change the magnitude of the applied voltage.

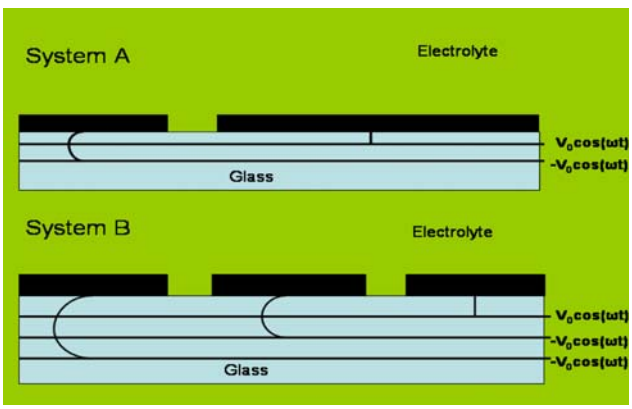

Fig. 1 Geometry of the electrodes of the standard asymmetric *system A* and the proposed *system B* (basic form)(not to scale)

2 Theory

AC electroosmotic flow is caused by the interaction of the tangential electric field over an electrode, with the charge in the double layer over that electrode. The system of interest is one of three parallel co-planar electrodes, which is repeated periodically, such as the one in Fig. 2. This is achieved by applying the same voltage $V_{\text{applied}} = V_0 \cos(\omega t)$ to one group of electrodes (say 1 and 2) and the opposite voltage $V_{\text{applied}} = -V_0 \cos(\omega t)$ to another group (electrode 3 in this case), so that a geometric asymmetry is created. In this way one can configure the direction of the asymmetry (or the degree of asymmetry in systems of more than three electrodes) in a system by regrouping the electrodes, for example in this case by grouping electrodes 2 and 3 together at an applied voltage $V_{\text{applied}} = -V_0 \cos(\omega t)$ and setting electrode 1 at $V_{\text{applied}} = V_0 \cos(\omega t)$. This effectively allows the control of the pumping direction and can be extended to systems of more electrodes grouped together, where the pumping velocity can also be controlled by simple switching of the voltages on the electrodes.

The model used here to simulate the operation of the system is one based on the Debye–Huckel theory for the double layer and is valid for low voltages only (Garcia-Sanchez et al. 2006). The effect of Faradaic currents is not taken into account. For further information regarding the theoretical model used here one might refer to Green et al. (2002) or Loucaides et al. (2005).

2.1 Electrical problem

In order to obtain the required electric field, Laplace's equation for the potential is solved:

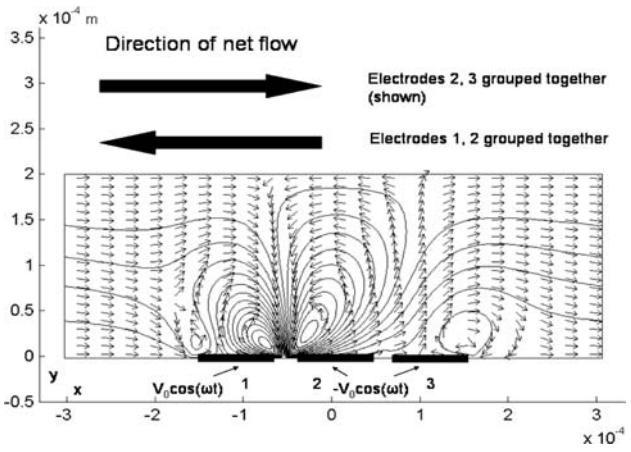

Fig. 2 Schematic of the configuration and operation of the proposed system (not to scale). The *arrows* and *streamlines* indicate the fluid flow direction

$$\nabla^2\phi = 0 \tag{1}$$

where φ is the electric potential. This is solved with the following boundary condition on the electrode (Green et al. 2002):

$$\sigma \mathbf{n}\nabla\phi_{\text{ep}} = \frac{\phi_{\text{ep}} - V_{\text{applied}}}{Z_{\text{DL}}} \tag{2}$$

where φ_{ep} is the potential at the outer edge of the electrical double layer, σ the fluid electrical conductivity, V_{applied} the value of the voltage applied at the electrodes, $Z_{\text{DL}} = \frac{1}{i\omega C_{\text{DL}}}$ the impedance of the double layer, $C_{\text{DL}} = \frac{\epsilon}{\lambda_{\text{Debye}}}$ the capacitance of the double layer (if the size of the compact layer is negligible), ω the angular frequency of the electric field and λ_{Debye} the Debye length on the electrode surface. The boundary condition used for all the electrodes is given by Eq. 2 (the applied voltage V_{applied} is different for each electrode depending on the grouping chosen). The two side boundaries of the domain have periodic boundary conditions (i.e. $\varphi(-l/2,0) = \varphi(+ l/2,0)$ where l = 600 μm here) and the rest of the boundaries are set to a homogeneous Neumann boundary condition $\mathbf{n} \cdot \nabla\varphi = 0$, where $\mathbf{n}$ is the vector normal to the surface. The electrode width is 100 μm, the channel depth is 200 μm, the interelectrode gap is 10 μm and the distance between electrode groups is 280 μm.

2.2 Fluid flow problem

The Navier–Stokes equations are solved, neglecting the inertial terms, to find the resulting fluid flow (under no external forces on the fluid):

$$\eta\nabla^2\,\vec{u} - \nabla p = 0 \tag{3}$$

$$\nabla\cdot\,\vec{u} = 0 \tag{4}$$

where η is the fluid viscosity, $\vec{u}$ the fluid velocity and p the fluid pressure. This has the following boundary condition for the fluid velocity on the surface of the double layer (which coincides with the electrode surface in the model geometry):

$$u_{\text{slip}} = -\frac{\epsilon}{4\eta}\Lambda\frac{\partial\left|\phi_{\text{ep}} - V_{\text{applied}}\right|^2}{\partial x} \tag{5}$$

where Λ is the ratio of the diffuse double layer potential drop over the total double layer potential drop. The parameter $\Lambda = \frac{C_{\text{Stern}}}{C_{\text{Stern}}+C_{\text{diffuse}}}$ is given by the ratio between the total capacitance and the diffuse double layer capacitance, and has been found experimentally for the system of interest here to be approximately 0.25 (Green et al. 2002). The properties of the system are summarised in Table 1. It should be noted that a potential V_0 = 0.5 V is used here to allow direct comparisons to be made with (Ramos et al. 2003), although it has been suggested that the assumptions made in the formulation might not be strictly valid at this operating voltage (Olesen et al. 2006). The linear approximation is used here because it is simpler to implement and has good accuracy at low voltages. The boundary condition at the surface of the electrodes is $u = u_{\text{slip}}$, where V_{applied} is different for each electrode, while the side boundaries are set to periodic boundary conditions and the boundaries at the interelectrode gaps are set to a no-slip condition.

Both the electrical and fluid flow problems are solved numerically using the method of finite elements with Comsol Multiphysics. A parameter useful for the analysis of such a system (and used here) is the nondimensional frequency $\Omega = \frac{\omega\epsilon L}{\sigma\lambda_{\text{Debye}}}$, where L is the device characteristic length (here the value used is twice the length of an electrode, 200 μm), λ_{Debye} the Debye length, σ the electrolyte conductivity and ω the angular frequency of the AC excitation. Another such parameter is the nondimensional velocity given by $U_{\text{non}} = 4\eta L u_{\text{slip}}/(\epsilon(\Delta V)^2\Lambda)$ where η is the fluid viscosity, u_{slip} the dimensional velocity and ΔV the potential difference between electrode groups, which is equal to $2V_0$ in this case.

3 Proposed method and system

Here the system of interest is one of parallel electrodes in a narrow channel, where both the electrode width and the channel depth are much larger than the electrode height so that the electrodes can be considered flat, and the length of the electrodes is much larger than their width, so that the problem can be treated as two-dimensional. The proposed system is related to the one shown in Fig. 1 (system A) and demonstrated experimentally in Brown et al. (2001) and theoretically in Ramos et al. (2003), with the significant difference that the asymmetry is configurable and not fixed into the system (system B).

In the simplest form, the proposed system consists of a repeating pattern of three identical electrodes as shown in Fig. 1 (system B) and in more detail in Fig. 2. The idea is that by applying a potential so that electrodes 2 and 3 are in anti-phase with electrode 1, an asymmetry of the electric field is created. This asymmetry is almost the same as if electrodes 2 and 3 were connected and the system was asymmetric in shape (system A in Fig. 1). This type of excitation will create circular flow patterns above the electrodes, which results in a net flow towards the larger group of electrodes, as shown in Fig. 2. The advantage of this system is that by applying the same potential on electrodes 1 and 2 this time, with electrode 3 in anti-phase,

Table 1 Electrolyte properties used in the simulations

Property	Value
Fluid viscosity (η)	1×10^{-3} Pa s
Relative permittivity of medium (ε_r)	80
Electrode peak potential difference ($2V_0$)	1 V
Λ	0.25
Permittivity of free space (ε_0)	8.8542×10^{-12} Fm^{-1}
Debye length (λ_{Debye})	3×10^{-8} m
Conductivity (σ)	1.23 mSm^{-1}

the asymmetry is reversed and therefore the flow is also reversed.

The fluid slip velocity over the electrodes at nondimensional frequency $\Omega = 6.03$ is shown in Fig. 3. It can be seen that by using different grouping of the electrodes it is possible to reverse the asymmetry and therefore the flow.

The pumping velocity is defined here as

$$U_p = \frac{1}{l}\int_{-l/2}^{l/2} u_{\text{slip}}\mathrm{d}x \tag{6}$$

where l is the length of the periodic segment of the device and u_{slip} the slip velocity at the electrode surface, as found by Eq. 5, with $u = 0$ at the gaps between electrodes. The nondimensional pumping velocity for system A is plotted against the nondimensional frequency in Fig. 4 and compared to the results obtained by Ramos et al. (2003, Fig. 9) for a system with the form shown in Fig. 1 (system A),

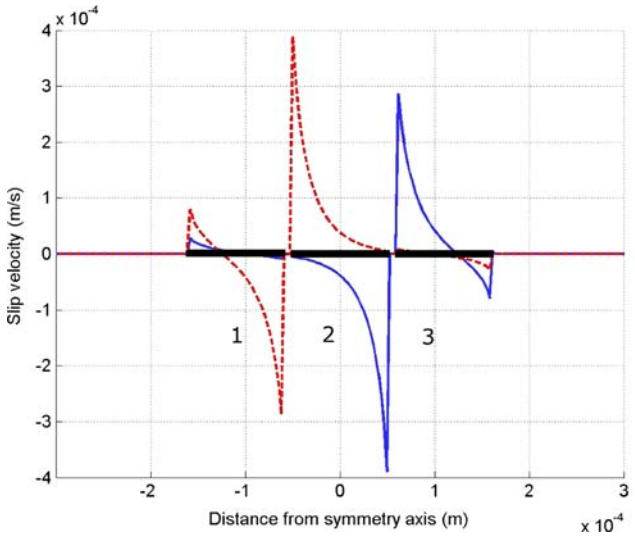

Fig. 3 Flow over the electrodes for two cases. *Dashed line* is for electrodes *2* and *3* grouped together, *solid line* for electrodes *1* and *2* grouped together. The electrode position is also indicated on the figure

with a nondimensional interelectrode gap $G_1 = 0.1$. This was done for verification purposes and the results were found to be in good agreement with the results obtained in Ramos et al. (2003). On the same plot in Fig. 4 the solid line is for system B, the system proposed here, with the electrode dimensions adjusted to (width of first electrode) $W_1 = 0.3$, (gap after first electrode) $G_1 = 0.1$, $W_2 = 0.6$, $G_2 = 0.1$, $W_3 = 0.3$ and $G_3 = 1$ in order to be consistent with the dimensions used in Ramos et al. (2003), and the channel height set to 200 to approximate an infinite channel height such as in Ramos et al. (2003)(note that the above parameters are nondimensional). It can be seen clearly in this plot that the effect of using the triple electrode system is a 10% reduction in velocity at the peak, while this is lower for other frequencies. This small drop in performance is more than compensated for by the added convenience of being able to alter the flow direction.

4 Other electrode structures

It has been demonstrated here that it is possible to construct a system with controllable asymmetry by using at least three identical electrodes per periodic array set. It is also possible to construct more interesting systems by adding more electrodes in the periodic array. For example, one could make this array out of four electrodes, and group 1, 2 and 3 together in terms of excitation, or 2, 3 and 4 to reverse the flow. Larger numbers of electrodes give the possibility of controlling the pumping velocity in a stepwise manner solely by inverting the polarity of the applied voltage on the electrodes.

For example, in a five-electrode array, grouping the first four or first three electrodes together would give pumping velocity in the same direction but of different magnitude. Therefore control of the pumping velocity can be achieved by simple switching between $V_0\cos(\omega t)$ to $-V_0\cos(\omega t)$ on certain electrodes, which minimises the required power circuitry and hence constitutes a great advantage for such systems. The velocities in the two cases for such a system are demonstrated in Fig. 5. The electrodes are of length 80 μm each while the gap between them is 25 μm. The array periodic length is the same as in the three-electrode system described before, equal to 600 μm.

The pumping velocity when one electrode is a group on its own is 4.638×10^{-6} ms^{-1} while it becomes 2.102×10^{-6} ms^{-1} when the first two are grouped together, due to the decrease in the asymmetry of the system (at $\Omega = 4.12$). This observation demonstrates the fact that the pumping velocity can be controlled by varying the system asymmetry. The flow rate F can be obtained by $F = \frac{u_{\text{slip}} \times (\text{Area}_{\text{cross-section}})}{2}$, given that the channel height is much smaller than the electrode length (the electrode length

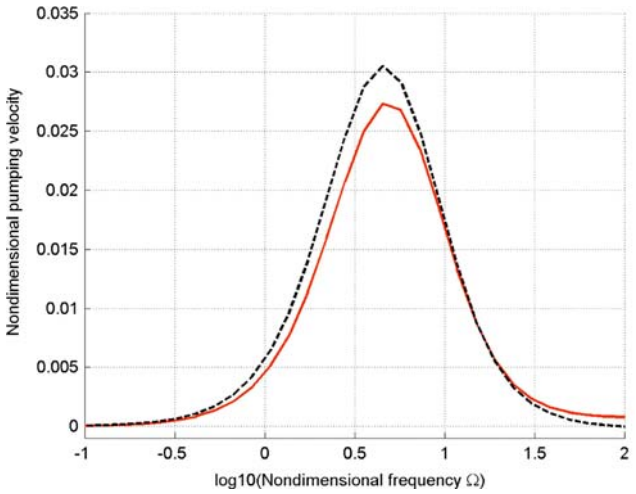

Fig. 4 Nondimensional pumping velocity against nondimensional frequency. *Black dashed line* is for the case plotted in (Ramos et al. 2003, corresponds to Fig. 9 top curve for nondimensional interelectrode gap $G_1 = 0.1$), *solid red line* is for the device proposed here

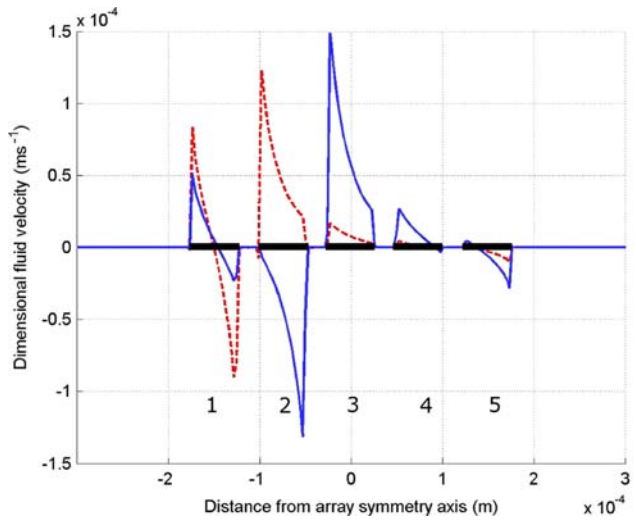

Fig. 5 Dimensional slip velocity against distance from symmetry axis. *Dashed line* is for the case where electrodes *2–5* are grouped together (electrode *1* constitutes the other group), *solid line* for the case where electrodes *3–5* are grouped together (electrodes *1* and *2* form the other group). The electrode position is indicated on the plot

being the dimension perpendicular to Fig. 1 as viewed here). It is clear that increasing the number of electrodes in the length of one period will give a higher level of control on the system, as well as the ability to introduce more complex phenomena into the system.

It must be stated here that in terms of system fabrication, the proposed design requires an extra layer for every two electrodes added per periodic array, in order to accomodate the electrode connections. This means that there is an extra manufacturing cost incurred compared to the planar asymmetric electrode arrays. What also has to be noted is the alternative method of using travelling wave devices for fluid pumping. This is superior in terms of efficiency and can be realised by a two layer design. The proposed design can be readily implemented on travelling wave arrays by electrode grouping as described here (where three electrodes out of four are used and one is left as a spacer) and is a possible mode of operation in the case when a multiphase supply is not available for portable micro-devices. In order to realise the application of this method to existing devices, one could envisage the replacement of the two asymmetric concentric electrodes in Bown and Meinhart (2006) with three concentric electrodes of equal width. That would enable the reversal of the flow at a given voltage and therefore would allow the device to operate with more flexibility.

Another possible use of the proposed system could be in the local control of the flow direction in microfluidics networks. One could think of such a system to be similar to the one proposed by Gitlin et al. (2003), the difference being that the electrode arrays are replaced by the arrays proposed here. In this way the direction of the flow can be changed in a cross-shaped channel intersection by changing the direction of flow at each array and therefore at each channel. This also has applications in mixing, where the change in flow direction facilitates it.

5 Conclusions

A novel method has been demonstrated that enables the creation of configurable geometric asymmetries. This method has interesting applications in AC electroosmotic pumping at low voltages. Initial numerical simulations of a system designed using the described method, show that it is possible to produce inversion of the pumping velocity direction at low voltages, unlike systems where the asymmetry is fixed into the system. Such systems are particularly useful in microfluidics pumping applications where the use of low voltages is required, as in the local control of flow in microfluidic networks, and the pumping of secondary flows that can enhance stirring and mixing.

Acknowledgements The authors wish to acknowledge the financial support of the Cyprus Research Promotion Foundation (grant number PENEK 0505/24).

References

Ajdari A (2000) Pumping liquids using asymmetric electrode arrays. Phys Rev E 61(1):R45–R48

Bazant MZ, Ben Y (2006) Theoretical prediction of fast 3d ac electroosmotic pumps. Lab Chip 6:1455 – 1461

Bazant MZ, Squires TM (2004) Induced-charge electrokinetic phenomena: theory and microfluidic applications. Phys Rev Lett 92:066101

Bown MR, Meinhart CD (2006) Ac electroosmotic flow in a dna concentrator. Microfluid Nanofluid J 2(6):513–523

Brown ABD, Smith CG, Rennie AR (2001) Pumping of water with ac electric fields applied to asymmetric pairs of microelectrodes. Phys Rev E 63:016305

Cahill BP, Heyderman L, Gobrecht J, Stemmer A (2004) Electro-osmotic streaming on application of traveling-wave electric fields. Phys Rev E 70:036305

Garcia-Sanchez P, Ramos A, Green N, Morgan H (2006) Experiments on ac electrokinetic pumping of liquids using arrays of microelectrodes. Dielect Elect Insul IEEE Trans 13(3):670–677

Gitlin I, Stroock AD, Whitesides GM, Ajdari A (2003) Pumping based on transverse electrokinetic effects. Appl Phys Lett 83(7):1486–1488

Green NG, Ramos A, Gonzalez A, Morgan H, Castellanos A (2002) Fluid flow induced by nonuniform ac electric fields in electrolytes on microelectrodes iii Observation of streamlines and numerical simulation. Phys Rev E 66:026305

Lastochkin D, Zhou R, Wang P, Ben Y, Chang H (2004) Electrokinetic micropump and micromixer design based on ac faradaic polarization. J Appl Phys 96(3):1730–1733

Loucaides N, Georghiou GE, Charalambous CD (2005) Manipulation of nanoparticles by electronic methods: model development and control problem formulation. In: The 3rd international symposium on nanomanufacturing, vol 1, pp 69–73

Olesen L, Bruus H, Ajdari A (2006) Ac electrokinetic micropumps: the effect of geometrical confinement, faradaic current injection, and nonlinear surface capacitance. Phys Rev E 73(5):056313

Ramos A, Morgan H, Green NG, Castellanos A (1998) Ac electrokinetics: a review of forces in microelectrode structures. J Phys D 31:2338–2353

Ramos A, Morgan H, Green NG, Castellanos A (1999) Ac electric-field-induced fluid flow in microelectrodes. J Colloid Interface Sci 217(2):420–422

Ramos A, Gonzalez A, Castellanos A, Green NG, Morgan H (2003) Pumping of liquids with ac voltages applied to asymmetric pairs of microelectrodes. Phys Rev E 67:056302

Ramos A, Morgan H, Green NG, González A, Castellanos A (2005) Pumping of liquids with traveling-wave electroosmosis. J Appl Phys 97:084906

Studer V, Pépin A, Chen Y, Ajdari A (2004) An integrated ac electrokinetic pump in a microfluidic loop for fast and tunable flow control. Analyst 129:944–949

Urbanski JP, Thorsen T, Levitan JA, Bazant MZ (2006) Fast ac electro-osmotic micropumps with non-planar electrodes. Appl Phys Lett 89:143508

Wu J (2006) Biased ac electro-osmosis for on-chip bioparticle processing. IEEE Trans Nanotechnol 5(2):84 – 89

Wu J, Ben Y, Chang H (2005) Particle detection by electrical impedance spectroscopy with asymmetric polarization ac electroosmotic trapping. J Microfluid Nanofluid 1(2):161–167