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Electrostatic Force Modulation as a Flow Control Mechanism in Microfluidic Devices

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Abstract: Electrostatic actuation is common in micro machined flow control devices, with most applications depending on movements of a diaphragm or cantilever. In this paper, we present a novel technique of electrostatic actuation of confined colloidal systems in a capillary. Such actuators may find applications as microfluidic check valves or switches and might even function as pumps. The governing principle of this application is the modulation of the interaction forces between two similarly charged colloidal particles by changing the surface potential (or surface charge density) of the confining walls of the cylinder. The variation of the electrostatic forces between the colloidal particles induced by the modulation of the cylinder surface potential is likely to create a linear machine. The oscillation of the colloidal particles due to the variations of the interaction force may be utilized for controlled delivery of fluids in devices like microarrays and labs-on-a-chip. In this study, we present simulations of the forces that can be generated in such systems, and explore some of the potential uses and benefits of such actuators.

1. INTRODUCTION

Development of microvalves and pumps for controlled delivery of small volumes (μl to nl) of fluids has received significant attention over the recent years, specifically for rapid chemical analysis and detection using microfluidic chips, for drug-delivery applications, or for delivery of coolants in microchips[1-3]. From amongst the different actuation mechanisms, electrostatic actuation tends to be the simplest from the viewpoints of

implementation and operation[2]. Traditional designs of microvalves or micropumps employing electrostatic actuation resort to using a diaphragm or a cantilever that is subject to repeated cycles of stretching or bending stresses [2, 4]. Such processes may limit the life of such components in a microdevice.

A considerable number of microfluidic applications involve dielectric fluids, which contain dissolved ions. If we suspend colloidal particles (small particles $< 5 \mu\text{m}$ in diameter) in a small volume of such a fluid, these particles can acquire a surface charge, the magnitude of which depends on the surface properties of the particles [5]. Two similarly charged particles suspended in an ionic dielectric generally repel each other. Considerable attention has been devoted toward modeling, characterizing, and measuring the nature of these electrostatic forces under a wide range of physico-chemical conditions[6, 7]. It has also been shown that confining these particles in a small domain with charged boundaries, for instance, between two parallel electrodes or in a narrow capillary enclosure, can substantially modify the interaction forces between them [8, 9].

The primary objective of this study is to modulate the colloidal force between two particles by altering the charges or potentials on the wall of the confining domain, thereby inducing a linear motion between the particles. A significant advantage of such a colloidal device over traditional designs involving cantilevers or diaphragms stems from the absence of stretching, bending, or frictional forces that can lead to failure of the device. In this paper, we outline the mechanisms of such force modulation between two spherical colloidal particles induced by the charged confining walls of a cylindrical capillary and qualitatively investigate how the force depends on the charging behavior of the confining domain boundary as well as some of the key physico-chemical conditions of the system. Based on these theoretical results, we suggest application of the system as an electrostatic actuator that might function as a microvalve.

2. GOVERNING PRINCIPLES OF THE COLLOIDAL MICROVALVE

A schematic representation of the proposed colloidal microvalve is shown in Fig.1. The basic construction should involve fixing a spherical colloidal particle in a cylindrical capillary, and aligning a second colloidal particle in the capillary between two wedges or guides. The second colloidal particle can move horizontally between the two guides. Depending on its two extreme positions (the “off” position shown as the solid sphere and the “on” position shown as the dashed outline), the sphere will allow the fluid entering the capillary through the inlet port to flow through one of the two

exit ports. Our objective is to study the extent of force modulation between the two spherical particles that can be achieved by turning the cylinder surface potential “on” and “off”.

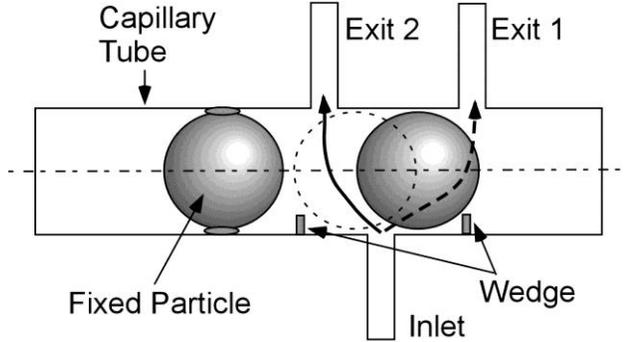


Figure 1. Schematic representation of a colloidal microvalve.

3. INTERACTION ENERGY AND FORCE BETWEEN TWO SPHERES

The interaction energy between two spherical colloids in an infinite domain containing an electrolyte solution is given by the Derjaguin-Landau-Verwey-Overbeek (DLVO) potential, which comprises an attractive Lifshitz-van der Waals (LW) and an electrostatic double layer (EL) interaction [10, 11]. The EL interaction may be attractive or repulsive depending on the physico-chemical conditions and the surface charge on the particles. For similarly charged particles, the EL interaction is generally repulsive. The total DLVO interaction energy between two particles of diameter σ separated by a dimensionless center-to-center distance $R (= r/\sigma)$ is [12]:

$$U_{DLVO}(r) = U_{LW} + U_{EL}$$

$$= -\frac{A}{12} \left[\frac{1}{R^2} + \frac{1}{R^2 - 1} + 2 \ln \left(1 - \frac{1}{R^2} \right) \right] + \frac{Q^2}{4\pi\epsilon_0\epsilon_r} \frac{\exp[-\kappa(r - \sigma)]}{r(1 + \kappa\sigma/2)^2} \quad (1)$$

where A is the Hamaker constant, Q is the particle charge, ϵ_0 is the permittivity of vacuum, and ϵ_r is the dielectric constant of the solvent. The parameter κ governs the decay behavior of the electrostatic interaction, and is known as the inverse Debye length. The Debye length depends on the

electrolyte concentration of the suspending medium through the relationship [12]:

$$\kappa^{-1} = \left(\frac{\varepsilon_0 \varepsilon_r kT}{2000 N e^2 z^2 C} \right)^{1/2} \quad (2)$$

where k is the Boltzmann constant, T is the absolute temperature, N is the Avogadro number, e is the magnitude of electronic charge, z is the charge number of the ion for a symmetric ($z : z$) electrolyte, and C is the molar concentration of the electrolyte.

The interaction energy between two particles can be altered by changing the electrolyte concentration, which modifies the Debye screening length. Furthermore, the particle charges can be modified to change the magnitude of the colloidal interactions. These two effects on the net DLVO potential between two spherical colloids ($\sigma = 1 \mu\text{m}$) is depicted in Fig. 2, which plots the scaled interaction energy (U_{DLVO}/kT) against the scaled separation distance for different combinations of particle charge and screening length. The influence of electrolyte concentration is manifested through a change in slope of the interaction energy curve (the solid and the dashed lines). On the other hand, decreasing the particle charge by a factor of 10 causes an almost two orders of magnitude reduction in the overall interaction energy. These results, which were obtained for a Hamaker constant of $1 kT$ and $Q = 400e$, where e is the charge of an electron, show negligible influence of the LW attractions on the overall DLVO potential. The force between the two particles is obtained from the derivative of the interaction energy with respect to separation distance.

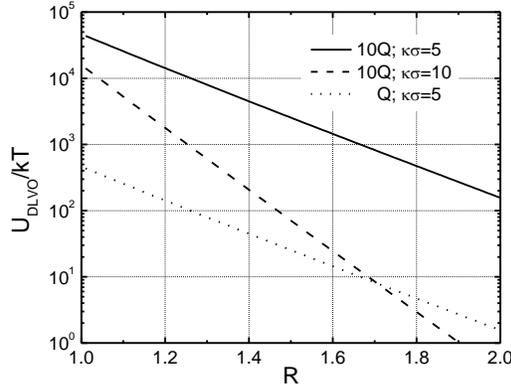


Figure 2. DLVO interaction energy between two equal spheres.

On the basis of the above results, it becomes discernable that the modulation of the electrostatic force by varying the surface charge densities on the colloidal particles can be an attractive means of achieving a linear movement of the colloidal particles, once these can be confined in a small domain. In the following, we discuss how confining the particles in a cylindrical capillary with charged walls can alter the charging behavior and the net electrostatic interaction energy between the colloidal particles.

4. COLLOIDAL INTERACTIONS IN A CHARGED CAPILLARY

The confinement of two colloidal particles in a cylindrical capillary will modify the electrostatic interaction energy between the particles. The extent of this modification will primarily depend on the surface potential of the cylindrical capillary wall. To assess the interaction energy for this geometry, we solve the Poisson-Boltzmann (PB) equation in the confined electrolyte intervening the cylinder and the colloidal particles. The governing PB equation for a symmetric electrolyte can be written as [7]:

$$\nabla^2\Psi = \kappa^2 \sinh(\Psi) \quad (3)$$

where Ψ is the dimensionless potential ($\Psi=ze\psi/kT$) and ψ is the electrostatic potential in the electrolyte. The parameter κ was defined earlier in Eq. (2).

Equation (3) was solved numerically in a cylindrical coordinate system to obtain the electrostatic potential and the field distribution in the confined electrolyte. The symmetry in the radial and angular coordinates was utilized to formulate the problem in a two-dimensional computational domain spanning one-half of the cylindrical space. Constant surface potential boundary conditions were applied on the cylinder wall and the spherical particle surfaces. Both spheres were assigned the same constant surface potential, while the cylinder surface potential was varied in different simulations.

Figure 3 shows the geometric details and the various boundary conditions used in the numerical solution of the governing equations. The solution was performed using finite element approximation employing FEMLab[®] and Matlab. A typical adaptive mesh required for solving the problem is also shown in Fig. 3. The governing equations were solved after scaling all linear dimensions with respect to the Debye length. Accordingly, the particle radius, a , and the cylinder radius, r , are represented in terms of dimensionless parameters κa and κr , respectively. In these scaled units, the problem becomes independent of the actual physical dimensions of the

particles and the cylinder, and all the scaled interaction energies and forces are applicable to different particle and cylinder radii, provided the ratio r/a remains fixed.

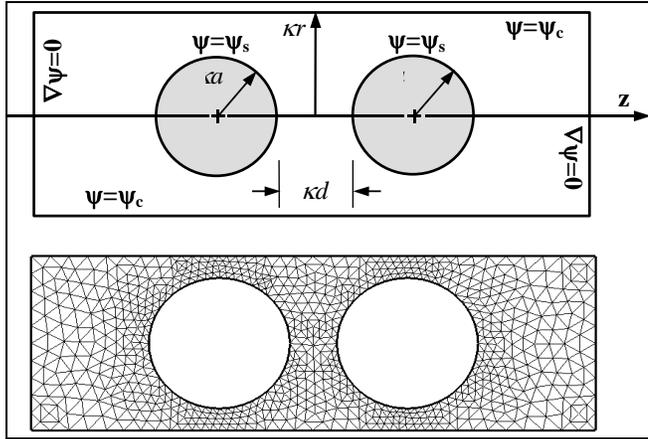


Figure 3. Top: Schematic representation of the computational domain and boundary conditions; Bottom: An adaptive finite element discretization of the domain

Some representative potential and electrostatic field distributions in the confined electrolyte corresponding to cylinder surface potentials of zero and *ca.* 25 mV (corresponding to the “off” and “on” configurations of the device, respectively) are depicted in Fig. 4. In both cases, the surface potentials on the spheres are fixed at 25 mV. The potential distribution in the domain (upper two plots in Fig. 4) varies markedly corresponding to the “off” and “on” states of the cylinder surface. For a zero surface potential on the cylinder, the potential decreases rapidly from the sphere surfaces, while the electrostatic potential distribution varies more modestly when the cylinder surface potential is 25 mV. This alteration in the potential distribution changes the electrostatic field quite remarkably, as shown in two lower plots in Fig. 4. Noting that the electrostatic field is obtained from the spatial gradient of the potential ($\mathbf{E} = \nabla\psi$), we can immediately recognize that the electrostatic field distribution in the “on” configuration is quite modest, and the Maxwell stresses are significantly lower on the particles in the “on” configuration. The magnitudes of the electrostatic fields shown in the contour labels clearly suggest an order of magnitude suppression in the field strength around the individual spheres when the voltage on the cylinder wall is turned on.

The net electrostatic force on a colloidal particle is determined by integrating the stress tensor on the particle surface. The stress tensor comprises an isotropic osmotic contribution and the Maxwell stresses arising

from the electrostatic field. Combining these, the electrostatic force on the movable colloidal particle is expressed as [13]:

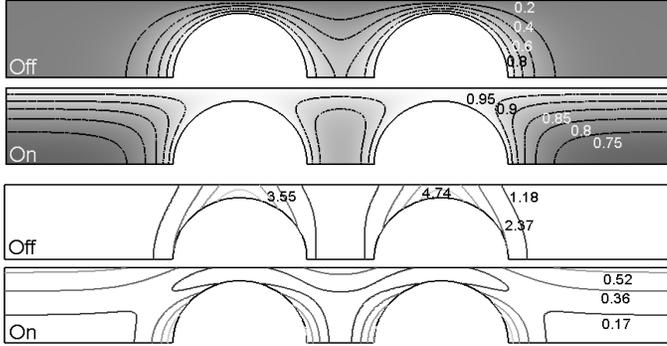


Figure 4. Distribution of the electrostatic potential (two upper shaded plots) and field strength (two lower contour plots) in the confined domain for the "off" and "on" configurations.

$$\mathbf{F} = \int_{Sphere} \left[\left(\Pi - \frac{1}{2} \epsilon_0 \epsilon_r \mathbf{E} \cdot \mathbf{E} \right) \boldsymbol{\delta} + \epsilon_0 \epsilon_r \mathbf{E} \mathbf{E} \right] \cdot \mathbf{n} dS \quad (4)$$

Here \mathbf{F} is the force acting on the sphere, \mathbf{E} is the electrostatic field vector, Π is the osmotic pressure difference between the electrolyte at the particle surface and the bulk electrolyte, \mathbf{n} is the unit outward surface normal, and $\boldsymbol{\delta}$ represents the unit diagonal tensor. The influence of changing the electrostatic field on the net colloidal force can be easily identified without explicitly evaluating the integrals. First, we note that the isotropic osmotic stress term vanishes when the osmotic pressure is integrated over the constant potential surface of the sphere [14]. Consequently, the integral of the stress tensor will solely comprise the electrostatic field terms. As the field strength diminishes when the cylinder surface potential is switched on, the net electrostatic force will also diminish compared to the off configuration.

It should be noted here that several earlier studies reported this lowering of the electrostatic force between two colloidal particles in a confined domain [8, 9, 15]. This study indicates that such forces can be modulated in MEMS devices quite easily, thereby allowing for the development of novel actuators that can function as microfluidic control devices. Since the moving part in this device is not being subject to repetitive strains (the entire colloidal particle moves in the altered force field), it should be able to

perform reliably over a considerably longer period compared to fixed component microdevices.

5. FROM PHYSICS TO FUNCTIONAL MICRODEVICES

The underlying physical principles of the microvalve proposed in this paper seem to provide a sound basis for a viable microdevice, although one must consider other factors that will influence the functionality of such a device. First, we have simply considered the two static situations corresponding to two different charged states of the cylindrical wall in these calculations, without considering the dynamic behavior of the system as the voltage on the wall is changed. Secondly, in these simulations, we have not considered the influence of the fluid flow, or the electrolyte polarization due to the charged surfaces of the spheres and the cylinder. Clearly, these two phenomena will influence the performance of the flow control device. The fluid flow around the spherical particles will induce hydrodynamic (drag) forces on the particle and can either complement the colloidal forces to enhance the response to the potential switching or can reduce the effect of switching. This effect can however, be controlled to a large extent by designing the inlet and outlet ports appropriately. Secondly, there can be an electroosmotic flow engendered by the polarization of the point charge carriers (ions) [5].

The influence of fluid drag and electroosmotic forces can be modelled by building in the appropriate physics of these effects in the governing equations. At the very least, this will involve a coupled solution of the Navier-Stokes (NS) equations for the electrolyte flow in the microchannel [16] and the Poisson-Boltzmann equation describing the electrostatic field. The formulation of the NS equations should be in the low Reynolds number domain, but should incorporate the electrical body forces and the osmotic stress distributions arising from the polarization of the electrolyte. The adoption of FEMLab[®] as the tool for solving the multiphysics based model greatly facilitates the process of exploring the parameter domain where the device can perform properly. Currently, work in underway in our laboratory to incorporate these effects and model the dynamics of the colloidal actuators for a variety of applications including electrostatically actuated micropumps, various types of check valves, and osmotic pumps.

6. CONCLUDING REMARKS

A colloidal microvalve based on the principles of electrostatic force modulation between two colloidal particles is proposed. Simulation of a simple realization of the proposed system, namely, two spherical colloidal particles confined in a cylindrical capillary, depicts the marked change in colloidal forces achievable by modulating the surface potential of the cylindrical capillary wall. The primary advantage of such colloidal actuators over traditional electrostatic actuator design stems from the absence of repetitive stretching or bending stresses on the device components, thereby prolonging the life of such devices. The proposed device is also fairly simple to implement, since it involves trapping two colloidal particles in a cylindrical or even a rectangular channel, the walls of which function as electrodes. Consequently, such flow control devices can be quite easily developed on a chip using standard lithographic techniques.

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