PERFORMANCE CHARACTERIZATION OF AN INSULATOR-BASED DIELECTROPHORETIC MICRODEVICE

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Abstract

This study presents the effects of operating conditions on the dielectrophoretic behavior of polystyrene microparticles under insulator-based DEP (iDEP). Experiments were performed employing microchannels containing insulating structures that worked as insulators. The parameters varied were pH (8-9) and conductivity (25, 50 and 100 µS/cm) of the bulk medium and the magnitude of the applied field (200-850 V/cm). Optimal operating conditions in terms of pH and conductivity of the suspending medium were obtained, and the microdevice performance was characterized in terms of concentration factor and minimum electric field required (minimum energy consumption). This is the first report on improving iDEP processes when electroosmotic flow (EOF) is present and DC electric fields are employed. DEP and EOF have been studied extensively; however, this study integrates the effect of suspending medium characteristics on both electrokinetic phenomena. These findings will allow improving the performance of DC-iDEP microdevices achieving the highest concentration fold with the lowest energy consumption.

Introduction

Miniaturization has brought important advantages to bioseparation technology. Numerous fields, including environmental, clinical, pharmaceutical and biochemical, have beneficiated from the advances of microanalytical systems. There is a growing interest on the development of separation techniques that can applied in microscale. Miniaturization offers important advantages to analytical systems such as: lower cost, reduced sample and reagent consumption, short response time, greater sensitivity and portability. Dielectrophoresis (DEP), an efficient technique with great potential for miniaturization, is the movement of particles as a result of polarization induced by non-uniform electric fields and it can occur in AC or DC electric fields [1, 2]. DEP has been successfully applied for the manipulation and concentration of wide range of bioparticles [3]. The DEP force exerted on a particle depends on the magnitude and gradient of the applied field, and the properties of the particle and the suspending medium. The DEP force acting on a spherical particle is given by:

$$F_{DEP} = 2\pi\varepsilon_m r^3 \,\mathrm{Re}\left(f_{CM}\right) \nabla E^2 \qquad (1)$$

where ε_m is the permittivity of the suspending medium, *r* is the radius of the particle, *E* is the local electric field, and Re(f_{CM}) is the real part of the Clausius-Mossotti (CM) factor, in many practical systems, at frequencies below 100 kHz, the CM factor can be approximated in terms of the real conductivities [3]:

$$f_{CM} = \left[\frac{\sigma_p - \sigma_m}{\sigma_p + 2\sigma_m}\right] \qquad (2)$$

where σ_p and σ_m are the conductivities of the particle and the medium, respectively. The magnitude of Re(f_{CM}) depends on whether the particle is more or less conductivity than the medium. If Re(f_{CM}) is positive, then particles move to regions of highest field strength (positive dielectrophoresis); the converse is negative dielectrophoresis, where particles are repelled from these regions (negative dielectrophoresis). In this work, the suspending mediums with conductivities varying from 25 to 105 µS/cm were employed. The conductivity for polystyrene particles, can be calculated as follows [5]:

$$\sigma_p = \sigma_b + \frac{2\ Ks}{r} \qquad (3)$$

where σ_b is the bulk conductivity of the particle, $\sigma_b \approx 0$ for polystyrene, and Ks is the general surface conductance of the particle, typically 1 nS for polystyrene, and r is the radius of the particle [20]. Employing Equation (3), the conductivity of polystyrene particles having a diameter of 1 µm is calculated as 40 µS/cm. Employing Equation (2) is possible to calculate the Clausius-Mossotti factor for the 1-µm-diamteter polystyrene particles suspended in each one of the different bulk medium employed, the values of the CM factors are reported in Table 1.

Table 1. Clausius-Mossotti Factors for the 1 µm polystyrene particles employed in this study**.**

Conductivity of the polystyrene particles employed (1 µm)	Conductivity of the suspending medium	CM factor
40 µS/cm	25 µS/cm	+0.167
	50 µS/cm	-0.071
	105 µS/cm	-0.260

DEP is of second order with respect to the electric field; at low applied electric fields, low electric fields gradients are produced, which leads to negligible dielectrophoretic force; therefore, the applied electric field has to be high enough for DEP to become significant. The electrokinetic flow, which is proportional to the electric field, comprises the effects of electroosmosis and electrophoresis on particle motion relative to a fixed channel. Electrophoresis is the motion of charged particles when subjected to an electric field and electroosmotic flow is the motion of liquid induced by a capillary tube or microchannel when a DC electric field is applied. For that electroosmotic motion happen it is necessary that the channel or capillary walls posses a net charge in the presence of an electrolyte. In the present research work, microdevices made from glass were employed; glass surface has a net negative charge in the presence of an electrolyte. When the DC electric field was applied across the microchannel, the ions from the electrolyte formed a double layer over the glass surface; the ions from the double layer were attracted to the negative electrode, generating electroosmotic liquid flow. The electroosmotic flow velocity is defined as [2]:

$$v_{EO} = \mu_{EO} E \qquad (4)$$

where v_{EO} is the electroosmotic flow velocity, μ_{EO} is the electroosmotic mobility and E is the applied electric field. The velocity of the electroosmotic flow is controlled by the magnitude of the applied electric field, the zeta potential, and the fluid properties. The bulk or suspending medium properties have an effect on the zeta potential of the microchannel wall, which affects the electroosmotic mobility:

$$\mu_{EO} = \frac{\zeta \varepsilon_m}{\eta} \qquad (5)$$

where ζ is the zeta potential of the microchannel or capillary wall, and η is the viscosity of the suspending medium. The zeta potential depends greatly on the bulk medium properties (pH and conductivity). Electrophoresis is the movement of charged particles in the presence of an electric field; the electrophoretic velocity of a particle is defined as:

$$v_{EP} = \mu_{EP} E \tag{6}$$

where v_{EP} is the electrophoretic velocity, μ_{EP} is the electrophoretic mobility and E is the applied electric field. The current work presents a study of how the bulk medium properties affect the dielectrophoretic response of inert polystyrene microparticles is presented. Experimental work was carried out employing iDEP in microdevices fabricated from glass. It is expected that the results from this study will provide valuable information and guidelines to be used when designing and selecting the appropriate operating conditions for the concentration and manipulation of bioparticles in microdevices with iDEP.

Materials and Methods

Equipment description: Experiments series were conducted using the technique iDEP and a microfluidic chip made from glass. The microdevice contained 8 microchannels, microchannels, that were 10.16 mm long, 2 mm width and 10 µm deep (Figure 1). Each microchannel contained and array of cylindrical insulating posts; 440 µm of diameter arranged 520mm center-to-center and, 10 µm high. A “dove-tail” geometry was used for the fists row of posts in order to prevent particles from crashing against the posts and plugging the system.

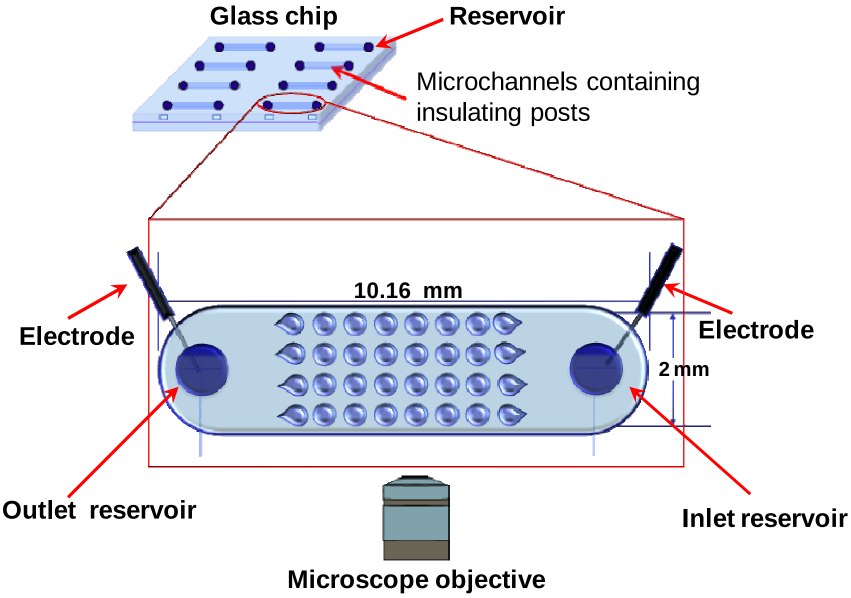

Figure 1. Representation of the glass chip and one of the microchannels.

A 3000 V high voltage sequencer, model HVS448 (LabSmith, Livermore, CA, USA) was used to apply electric fields. The particle-image recording system was an inverted 10X video epifluorescence microscope with a blue light-emitting diode ring illuminator, model SVM340 (LabSmith, Livermore, CA). Carboxylated-modified polystyrene microspheres 1-µm in diameter (Invitrogen, Carisbald, CA,USA) were used as model particles for dielectrophoresis. These microparticles were selected due to their robustness and availability as fluorescent probes. The excitation/emission maximums for these microspheres are 505/515 nm. For DEP experiments, the spheres were prepared by adding 10 µL of beads to 2 mL of deionized water. The bead suspension was sonicated for 20 min to break up agglomerates. The microchannel was filled with aqueous solution, whit adjusted pH and conductivity. The pH of this solution was adjusted to a value of 8.0 or 9.0 by adding NaOH and, the conductivity to values of: 25, 50 and 100 µS/cm, by adding K_2HPO_4. Different values of conductivity and pH were used to assess the effect of these parameters on the dielectrophoretic response of particles. A sample of microparticles was introduced at the inlet reservoir, the electrodes were placed at the inlet and outlet microchannel; subsequently applies the electric field. The dielectrophoresis was initiated by applying high voltage across selected channels. The dielectrophoretic behavior of the fluorescent polystyrene particles was recorded in the form of videos and pictures by employing an optical microscope.

Results and Discussion

Experiments were performed by slowly ramping to observe the influence to the electric field to achieve dielectrophoretic trapping. Shown in Figure 2 are some results obtained with different pH and conductivity of the suspending medium. It can be observed from Figure 2a (pH = 8, σ= 25 µS/cm) that the polystyrene particles inside de microchannel because no electric field is being applied. Figure 2b illustrates particles under electrokinetic flow when an electric field of 200 V/cm is applied using the same suspending medium. By increasing the applied electric field to 500 V/cm (Figure 2c) some negative dielectrophoretic trapping is observed, because particles are being concentrated at the narrow region between the cylindrical posts. Augmenting the applied electric field to 650 V/cm (Figure 2d), produced strong dielectrophoretic tapping. Figures 2b to 2d show how the dielectrophoretic response of the microparticles depends on the magnitude of the applied DC electric field.

Suspending medium conductivity effect

The effect of the conductivity of the suspending medium can be analyzed by observing the results in Figures 2d and 2e, obtained when E=650 V/cm and pH of 8, and conductivity of 25 and 100 µS/cm, respectively. By increasing the conductivity from 25 (Figure 2d) to 100 µS/cm (Figure 2e) it is possible to observe a stronger dielectrophoretic trapping. This is due to an increment on the magnitude of the negative CM factor (Equation 2 and Table 1). A greater magnitude of the negative CM factor means a greater magnitude of the negative dielectrophoretic force exerted on the particles.

Suspending medium pH effect

The dielectrophoretic response of the microparticles is strongly affected by the pH of the suspending medium. In this study, glass microdevices were employed with suspending medium with pH of 8 and 9. Glass surfaces have a negative zeta potentials, therefore the magnitude of the electroosmotic flow increases with pH [6]. The effect of pH can be observed by comparing the results shown in Figures 2e and 2f, obtained with E= 650 V/cm, σ = 100 µS/cm and pH of 8 and 9, respectively. The dielectrophoretic force in the results presented in Figure 2e is stronger that the dielectrophoretic force of the results presented in Figure 2f. Decreasing the pH of the suspending medium, decreases the minimum applied electric field necessary to achieve dielectrophoretic trapping. An increment in the pH of the suspending medium favors electroosmotic flow, which negatively affects dielectrophoretic trapping. The higher the pH of the suspending medium, the higher the number of hydroxyl ions (OH^-), which results in greater desprotonation of silanol groups on the glass surface, leading to a higher zeta potential that results in a higher electroosmotic mobility [7].

A set of experiments were carried out to observe the effect of conductivity and pH suspending medium on the dielectrophoretic trapping of microparticles. Experiments were performed by slowly increasing the applied field and observing the dielectrophoretic response, the objective was to determine the minimum applied field needed to obtain dielectrophoretic trapping by varying the conductivity and pH of the suspending medium. These results are presented in Figure 3. As it can be observed from Figure 3, the applied field required to achieve dielectrophoretic trapping decreases as a function of the conductivity suspending medium, this is in agreement with the results presented in Figures 2d and 2e. It can also be observed from Figure 3, that higher applied electric fields are required when employing a suspending medium with a higher pH. This is in agreement with the results presented in Figures 2e and 2f. The results in Figure 3 have the potential to be used to optimize dielectrophoretic processes, lower pH and higher suspending medium conductivity should be employed to minimize the energy applied to the system.

Another set of experiments was carried out to characterize the performance of the microdevice in terms of concentration factor. Concentration factor is an important parameter when employing dielectrophoretic devices as pre-concentrators. Experiments were performed by introducing a sample of microparticles into the microchannel, then applying a field of 200 V/cm, for 15 seconds; immediately after, a field of 500 V/cm was applied during 20 seconds, to produce strong dielectrophoretic concentration of particles. After 20 seconds the field of 500 V/cm was lowered to 200 V/cm, this released the particles from the dielectrophoretic traps by pushing them up with EOF, producing a moving plug of concentrated particles, that exited the post array. During the entire experiment, a video was taken at the exit of the post array, recording the particles passing through that area. Experiments were repeated by varying the pH and conductivity of the suspending medium. After the set of experiments was completed, the videos were analyzed using a software built in house to measure the fluorescence of the particles exiting the post array. From these fluorescence readings, and by comparing the fluorescence obtained before the field was applied to the fluorescence obtained by the plug of particles, it was possible to determine a concentration factor. The fluorescence of the plug of particles was much higher than the fluorescence of particles flowing under the influence of electroosmotic flow. The concentration factor was obtained by dividing the fluorescence of the plug of particles by the fluorescence of the particles flowing. The results obtained are presented in Figure 4. As one can observe, when employing the “ideal” conditions for dielectrophoresis, *i.e*. a conductivity of 100 µS/cm and a pH of 8 for the suspending medium, it was possible to increase the concentration almost 14 times. These results demonstrate the potential of dielectrophoretic microdevices to be employed as preconcentrators. Greater concentration factors are obtained by increasing the conductivity of the suspending medium, this is due to the increment of the CM factor. Greater concentration factors are obtained by decreasing the pH of the suspending medium, this is due to the lower electroosmotic flow obtained at lower pH.

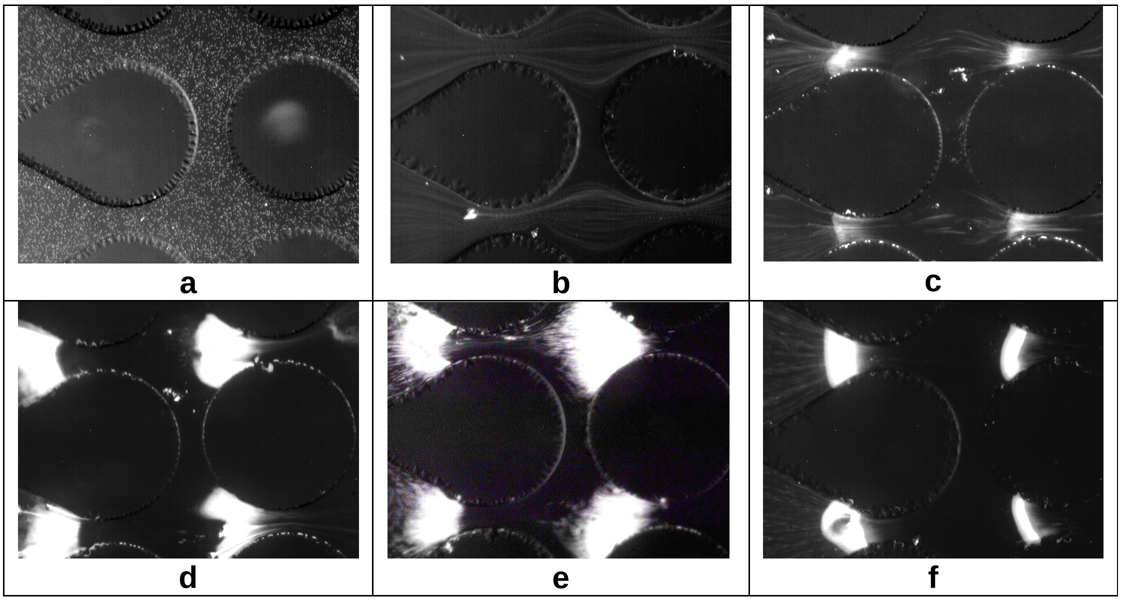

Figure 2. Pictures of particles inside the microchannel under dielectrophoretic effects. Flow direction is from left to right, post diameter is 400 µm; a) No dielectrophoresis present when E=0 V/cm at pH=8 and σ=25 µS/cm, b) electrokinetic flow of particles when E=200 V/cm at pH=8 and σ=25 µS/cm, c) some dielectrophoretic trapping when E=500 V/cm at pH=8 and σ=25 µS/cm, d) strong dielectrophoretic trapping E=650 V/cm at pH=8 and σ= 25 µS/cm, e) strong dielectrophoretic trapping when E=650 V/cm at pH=8 and σ=100 µS/cm, f) strong dielectrophoretic trapping when E=650 V/cm at pH=9 and σ=100 µS/cm.

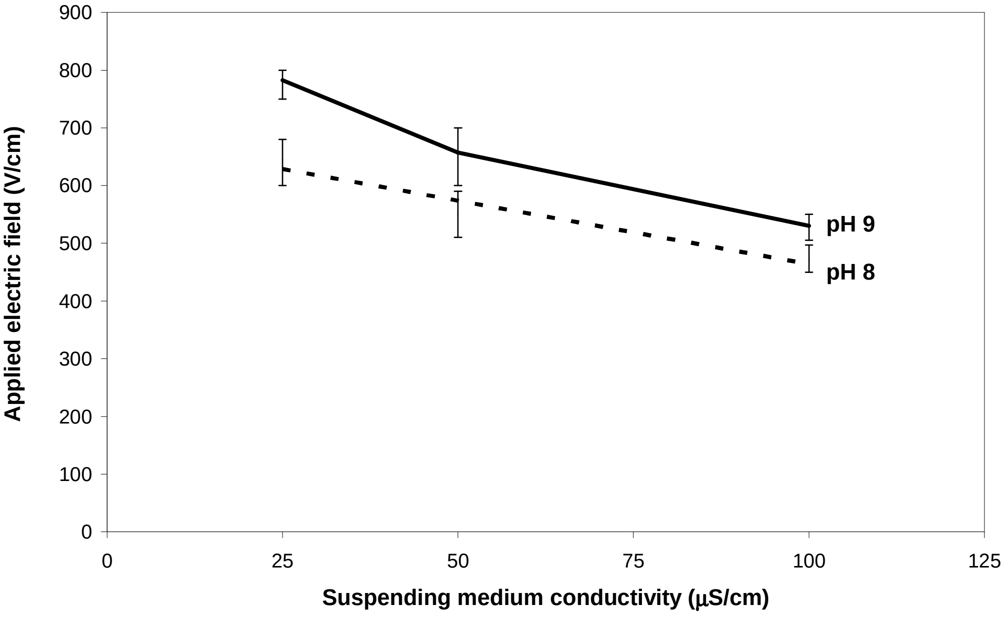

Figure 3. Minimum applied electric field required to achieve dielectrophoretic trapping of 1-µm in diameter polystyrene particles, as function of the pH and conductivity of the suspending medium.

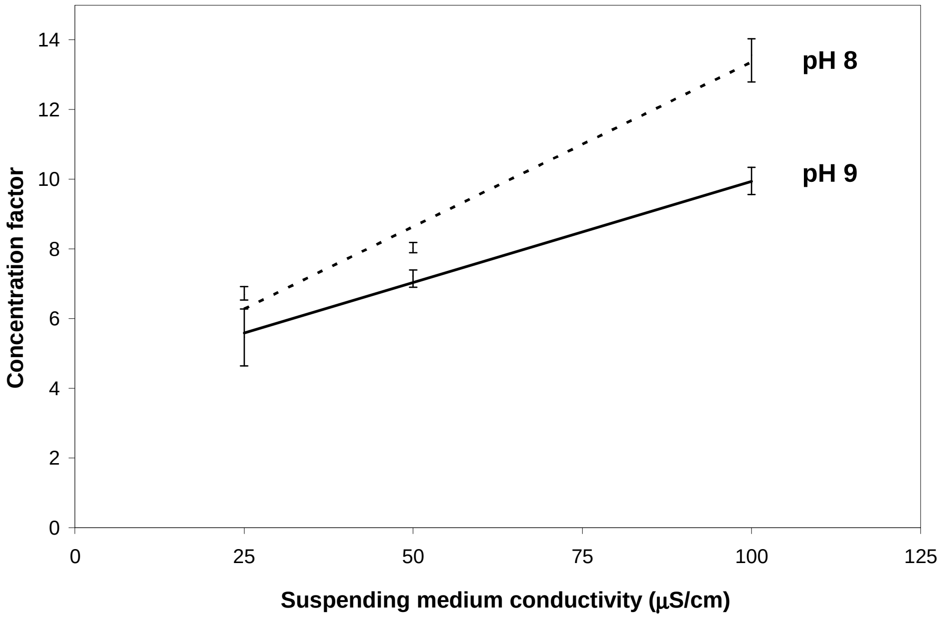

Figure 4. Concentration factor obtained for 1-μm in diameter polystyrene particles as function of the pH and conductivity of the suspending medium.

Conclusions

This research demonstrates experimentally how operating conditions influence the performance on an insulator-based-dielectrophoretic microdevice made from glass. The results demonstrated that microparticles can be trapped with negative DEP when DC electric fields are applied. Higher applied electric fields produced strong negative dielectrophoretic trapping of microparticles. Additionally, it was shown that increasing the conductivity of the suspending medium decreases the magnitude of applied electric field required to achieve dielectrophoretic trapping. Increasing the pH of the suspending medium produces an increased in electroosmotic flow, therefore, which increases the magnitude of the applied electric field required to achieve dielectrophoretic trapping. From the results can be concluded that the ideal operating conditions for iDEP when EOF is present is to employ the highest conductivity and lowest pH possible for the suspending medium. Utilizing these conditions decreases the energy consumption of the system and benefits the performance of the microdevice as a preconcentrator. The initial concentration of microparticles was increased 14 times when the optimal conditions were employed. These findings provide with guidelines for the design, operation and optimization of microdevices for iDEP.

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