Electrokinetic and Hydrodynamic Focusing/Switching in Microfluidics

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ABSTRACT

This paper presents an investigation into two crucial aspects of microfluidic applications, namely hydrodynamic /electrokinetic focusing and switching. This study commences by modeling the hydrodynamic/electrokinetic focusing phenomenon theoretically using potential flow theory. A new theoretical model is applied to predict the width of the focused stream. The results predicted by the theoretical model are shown to be in reasonable agreement with the experimental data and numerical simulation results. The paper then proceeds to study the hydrodynamic and electrokinetic switching functions systematically using both experimental and theoretical approaches. A simple control model for $1\times N$ electrokinetically pre-focused micro-flow switches is proposed. The study concludes by performing a systematic comparison of hydrodynamic and electrokinetic focusing/switching. The results of this study provide a useful methodology for the analysis of flow control in microfluidic devices.

Keywords: microfluicics, hydrodynamic focusing/switching, electrokinetic focusing/switching, micro-flow switch

1 INTRODUCTION

Recently, two-dimensional hydrodynamic and electrokinetic focusing approaches [1-2] have been demonstrated in a wide variety of applications, including in flow cytometers [3-4], diffusion-based mixers [5], and micro-flow switches [6-7].

The current research group has previously presented a simple model capable of predicting the width of two-dimensional hydrodynamically focused sample streams [8]. Hence, the principal aim of the current study is to develop a theoretical model to predict the width of electrokinetically focused sample stream. Furthermore, this study presents theoretical and experimental comparisons of hydrodynamic and electrokinetic focusing.

Hydrodynamic and electrokinetic switching are highly important techniques in microfluidic applications. The present study adopts numerical and experimental approaches to conduct a systematic investigation into the use of hydrodynamic and electrokinetic forces to realize flow switching in microfluidic devices. Additionally, this study presents a novel and simple control model based on electrokinetic forces. The effectiveness of the proposed control model is verified both numerically and experimentally.

2 EXPERIMENTAL SECTION

The present microchips were fabricated on commercially available soda-lime glass substrates measuring 22mm × 75mm × 1mm. A more detailed explanation of this fabrication process has been provided by the current study group in a previous publication [9]. Furthermore, the experimental setup employed in the current study of hydrodynamic and electrokinetic focusing/switching has been also provided by the current study group in previous publications [6-7].

3 FORMULATION

3.1 Governing Equations and Numerical Methods

A numerical model was developed to simulate the electrokinetic focusing and switching effects. This model was based on the Navier-Stokes equations modified to include an electrical driving force term in order to represent the interaction between the excess ions of the electrical double layer (EDL) and the external electric field. In this study, considering a thin EDL and assuming that there is no net electric charge density in the bulk liquid, the electrical driving force term in the equation of motion can be neglected. Also, while considering the effect of electroosmotic flow as the slip wall boundary conditions to the equation of motion, the wall slip velocity is determined by the Helmholtz-Smoluchowski equation, which is given by:

$$\vec{V}_{EO,slip} = \frac{\varepsilon\varepsilon_0\zeta}{\mu}\nabla\phi \qquad (1)$$

The externally applied electrical potential ϕ in microchannels is governed by the Laplace equation. Furthermore, in order to obtain information relating to the sample concentration distribution during the electrokinetic focusing and switching steps, the species convection-diffusion equation is solved. This study adopts the numerical method developed by the present authors to solve the governing equations together with their corresponding boundary conditions [10].

3.2 Theoretical Model

This present study develops a theoretical model to predict the width of the hydrodynamically and electrokinetically focused streams (see Figure 1). Details of a simple model to predict the width of the two-dimensional focused sample stream in hydrodynamic focusing have been reported previously [8]. According to the principles of mass conservation, and assuming that a fully developed laminar flow exists in outlet channel 4, and the relationship between $\bar{v}_c$ and $\bar{v}_4$ is $\bar{v}_c = X\bar{v}_4$, therefore, it can be shown that the width of the focused stream is given as:

$$d = \frac{D_4}{X\left((\bar{v}_2/\bar{v}_1)(D_2/D_1)+1+(\bar{v}_3/\bar{v}_1)(D_3/D_1)\right)} \quad (2)$$

where D_1, D_2, D_3 and D_4 are the widths of inlet channels 1, 2 and 3 and outlet channel 4, respectively; $\bar{v}_1$, $\bar{v}_2$, $\bar{v}_3$ and $\bar{v}_4$ are the average velocities inside inlet channels 1, 2 and 3 and outlet channel 4, respectively.

However, in order to obtain the width of the focused stream, the parameter X in Eq. 2 must be known. For hydrodynamic focusing, the fully developed velocity profile has a parabolic distribution. In a previous study [8], it was reported that $X = 1.5$, but it is valid only when $d << D_4$ (i.e. the sample flow rate is much smaller than the sheath flow rate). Hence, in this study, a more appropriate parameter X is used to remove this restriction, is given by:

$$X = \left(\frac{3}{2} - \frac{1}{2}\left(\frac{d}{D_4}\right)^2\right) \quad (3)$$

For electrokinetic focusing, the fully developed electroosmotic flow exhibits a "plug-like" velocity profile, i.e. $X = 1$.

Furthermore, to obtain the width of the electrokinetically focused stream, the velocities, $\bar{v}_1$, $\bar{v}_2$ and $\bar{v}_3$ in Eq. 5 must be known. According to the Helmholtz-Smoluchowski equation given in Eq. 1, the velocity of the electrokinetic flow within the microchannel is proportional to the externally applied electrical potential gradient. Assuming that $D_2 = D_3$, $\phi_2 = \phi_3$, $\phi_4 = 0$ (i.e. grounded), and ϕ_c can be determined in accordance with Kirchoff's laws [11], yields the following equations for predicting the normalized width of the electrokinetically focused stream:

$$\frac{d}{D_4} = \frac{1}{1+2\delta\eta\frac{(\alpha+1)(\phi_2/\phi_1)-\alpha}{1+2\alpha\delta\left(1-(\phi_2/\phi_1)\right)}}, \Re_{\min} \le \frac{\phi_2}{\phi_1} < \Re_{\max} \quad (4)$$

where $\delta = L_1/L_2$, $\sigma = L_1/L_3$, $\eta = D_2/D_1$, and ϕ_2/ϕ_1 is defined as the focusing ratio. In Eq. 4, when the normalized width of the focused stream is equal to "1" (i.e. there is no focusing effect), the focusing ratio, $\phi_2/\phi_1 = \alpha/(\alpha+1)$, is defined as the minimum focusing ratio, $\Re_{\min}$. Meanwhile, when the normalized width of the focused stream is equal to "0" (i.e. the focused stream is "pinched off"), the focusing ratio, $\phi_2/\phi_1 = 1 + 1/2\alpha\delta$, is defined as the maximum focusing ratio, $\Re_{\max}$.

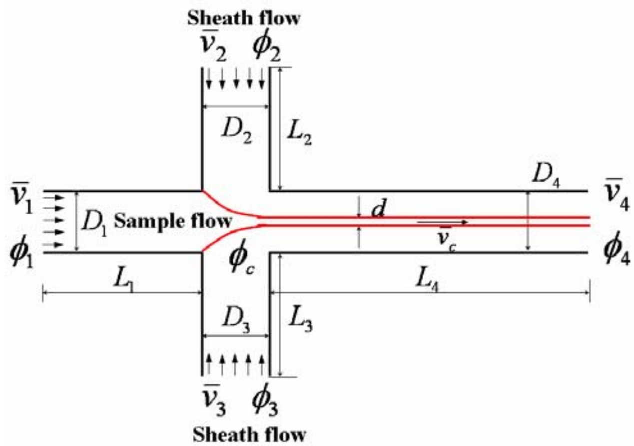


Figure 1: Schematic illustration of the flow focusing.

4 RESULTS AND DISCUSSION

4.1 Hydrodynamic and Electrokinetic Focusing Effects

This section of the paper discusses hydrodynamic and electrokinetic flow focusing inside the microchannel. A comparison between hydrodynamic and electrokinetic focusing is made. The results calculated using Eq. 2 are plotted in Figure 2 (Noted that $\bar{v}_2 = \bar{v}_3$). The experimental data relating to hydrodynamic and electrokinetic flow focusing are also presented in the same figure. It can be seen that these data are in good agreement with the results obtained from Eq. 2. It is note that the width of the electrokinetically focused stream is found to be 1.5 times that of the hydrodynamically focused stream when $d << D$ (i.e. $\bar{v}_2 >> \bar{v}_1$). This result can be attributed to the fact that the fully developed velocity profile of the hydrodynamic flow is distributed parabolically, while that of the electroosmotic flow is "plug-like".

4.2 Effect of Length Ratio α on Width of Electrokinetically Focused Stream

The objective of this section of the paper is to study the relationship between the width of the electrokinetically focused stream and the electrical potential applied to inlet channels 1, 2, and 3 and to the outlet port 4 (see Figure 1)). A model for predicting this relationship have been presented previously in Eq. 4. This section of the paper verifies the model experimentally.

From an inspection of Eq. 4, it is clear that the length ratio, α (i.e. L_4/L_1), plays an important role in determining the width of the sample stream. Figures 3(a)-(d) illustrate the relationship between the width of the electrokinetically focused sample stream and the focusing ratio (ϕ_2/ϕ_1) for the theoretical and experimental results obtained using length ratios of α =1, 2, 3 and 4, respectively. The width of channels 1, 2, 3, and 4 is assumed to be constant. Additionally, inlet channels 1, 2 and 3 are of equal length. From Figures 3(a)-(d), it is clear that the relationship between the width of the focused stream and the focusing ratio is dependent upon the length ratio α . In all cases, the focused stream width decreases as the focusing ratio increases. The experimental data are in reasonable agreement with the theoretical results predicted by Eq. 4.

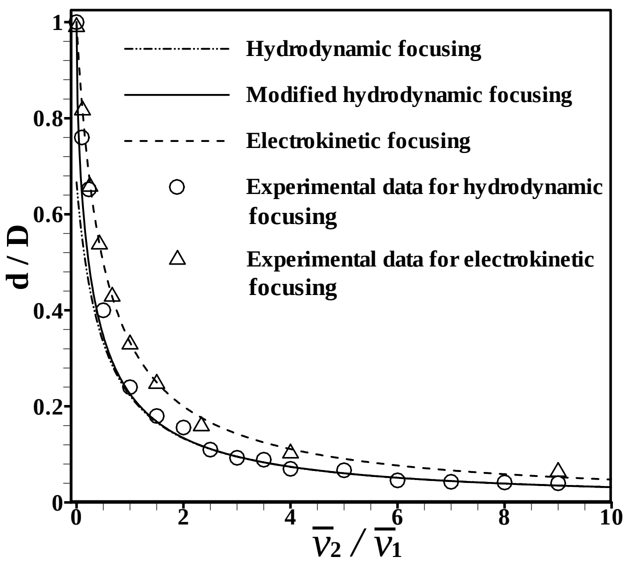


Figure 2: Comparison of normalized width of focused stream as function of relative sheath and sample flow rates for hydrodynamic and electrokinetic flow focusing.

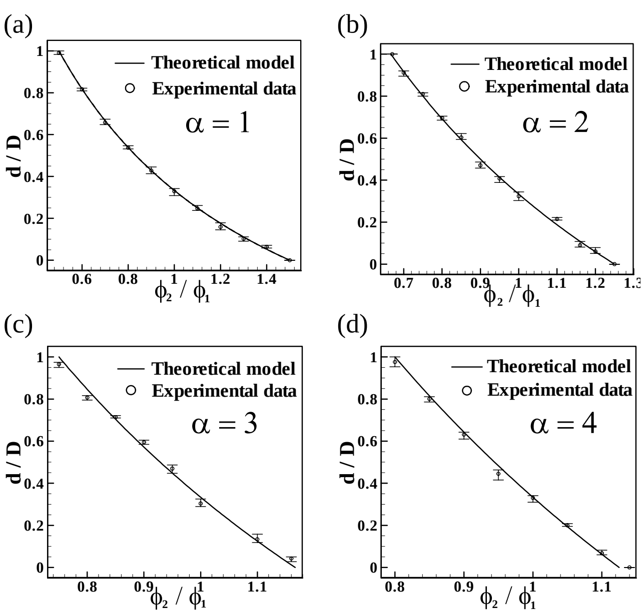


Figure 3: Effect of length ratio (α) on variation of width of focused stream as function of the focusing ratio.

4.3 Comparison of Hydrodynamic and Electrokinetic Flow Switching Based on "Flow-rate-ratio" Method

In this section of the paper, the pre-focused 1×3 micro-flow switch with one inlet sample port (S1) and three outlet ports (A, B, and C) shown in Figure 4 is used to compare the hydrodynamic and electrokinetic flow switching phenomena using the so-called "flow-rate-ratio" method [6]. Figure 5 presents the experimental and numerical results for hydrodynamic and electrokinetic flow switching. The operating conditions for the hydrodynamic and electrokinetic flow switching operations are listed in Tables 1 and 2, respectively. It is noted that the flow rates inside the inlet ports when performing electrokinetic flow switching are different from those established for the hydrodynamic flow switching case. However, the "flow-rate-ratios" (i.e. the ratio of the sheath and sample flow rates) are the same in both cases. Three different operational modes correspond to switching the sample flow to outlet ports A, B, and C, respectively. From Figure 5, it can be seen that the experimental data are in very good agreement with the numerical results. In the case of electrokinetic flow switching, as shown in Figures 5(a2) and 5(c2), it is clear that a small volume of the sample is carried into port B since the electrokinetic flow velocity is much lower than that of the hydrodynamic flow and then sample diffusion is un-eligible. Nonetheless, it can be seen that the streamlines of the sample flow all lie within the desired outlet channel.

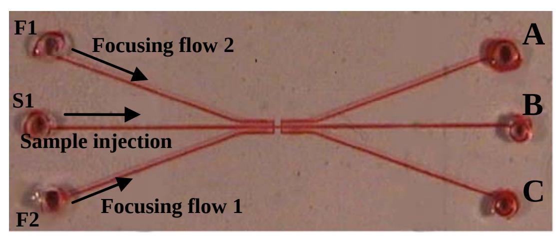
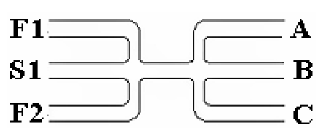
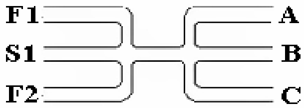


Figure 4: Photographs of Microchip capable of hydrodynamic or electrokinetic flow focusing and switching.



	Flow rate (mm/s) F1	F2	S1
(a1) mode A	3.54	20.06	2.95
(b1) mode B	11.8	11.8	2.95
(c1) mode C	20.06	3.54	2.95

Table 1: Operation conditions for hydrodynamically pre-focused 1×3 micro flow switches.



	Flow rate (mm/s)		
	F1	F2	S1
(a2) mode A	0.140	0.796	0.117
(b2) mode B	0.468	0.468	0.117
(c2) mode C	0.796	0.140	0.117

Table 2: Operation conditions for electrokinetically pre-focused 1×3 micro flow switches based on the “flow-rate-ratio” method.

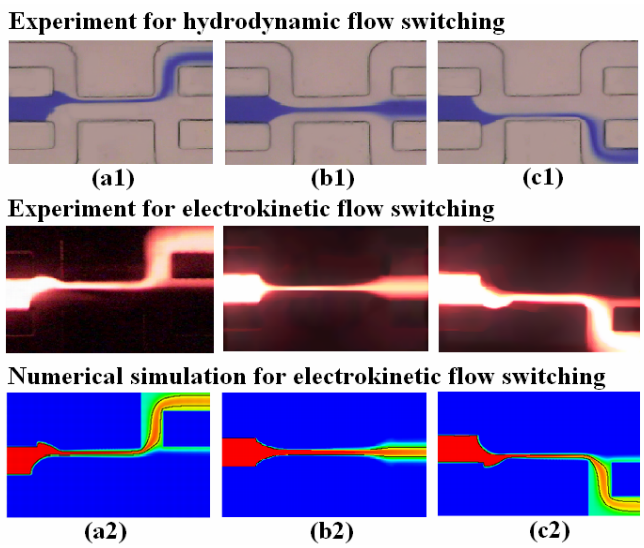


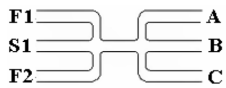
Figure 5: Comparison of experimental and numerical results obtained for hydrodynamically and electrokinetically pre-focused 1×3 micro flow switches.

4.4 Electrokinetic Flow Switching Based on “Electrokinetic forces”

This paper proposes a more straightforward control method for electrokinetic flow switching. By applying appropriate electrical potentials to the S1, F1, F2, A, B, and C ports, the sample flow can be pre-focused electrokinetically into a narrow stream and then directed precisely to the required outlet port. Figure 6 presents the experimental and numerical results for electrokinetic flow switching obtained using this approach. The operating conditions are listed in Table 3. The flow switching function implemented using electrokinetic forces is achieved by carefully specifying the outlet port to which electric grounding is to be applied.

5 CONCLUSIONS

In the present study, a simple theoretical model has been developed and is capable of predicting the width of the focused stream. The comparison between hydrodynamic and electrokinetic focusing has been made. The hydrodynamic and electrokinetic switching functions have also been investigated using both numerical and experimental approaches. It has been shown that the “flow-rate-ratio” method is capable of controlling the flow switching in both cases. An alternative model based on electrokinetic forces has also been proposed for flow switching. This simple model is significantly more straightforward than the “flow-rate-ratio” method when applied to the switching of focused sample streams to a desired outlet port.



	Electrical potential (kV)					
	F1	F2	S1	A	B	C
(a3) mode A	0.57	0.57	0.5	0	floating	floating
(b3) mode B	0.57	0.57	0.5	floating	0	floating
(c3) mode C	0.57	0.57	0.5	floating	floating	0

Table 3: Operation conditions for 1×3 electrokinetically micro flow switches based on electrokinetic forces.

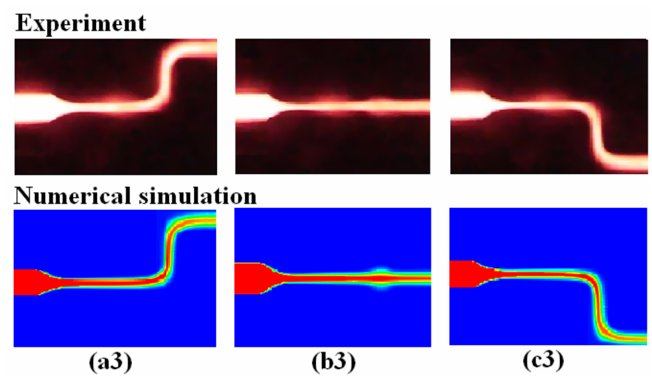


Figure 6: Experimental and numerical simulation results of electrokinetically pre-focused 1×3 micro flow switches.

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