

# OPTIMUM PECLET NUMBERS FOR ACCURATE MEASUREMENT OF ELECTROSMOTIC MOBILITY OF COMPLEX DNA BUFFERS IN MICRO/NANOFLUIDICS

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## ABSTRACT

In this paper, optimum Peclet number for the measurement of electroosmotic mobility with controlled errors in current-monitoring method was systematically investigated. A simple silicon based microchannel was fabricated for the experiments. Experiments and theoretical analysis of electroosmotic flow of both simple (NaCl) and complex electrolytes (concentrated Tris-Borate-EDTA buffer) was conducted to investigate the Peclet number effects on the error of electroosmotic mobility measurements. The results show that minimum Peclet number exist for desired accuracy.

**KEYWORDS:** Electroosmotic mobility, Peclet number, current-monitoring method, TBE, micro/nanofluidics

## INTRODUCTION

Electroosmotic flow (EOF) is one of the important methods to control the flow in micro/nanofluidics. When fluidic channels go from micron to nanometer size, the surface properties become the key factors for controlling the electroosmotic flow [1]. Therefore, the characterization of surface properties (hydrophobicity, zeta potential, etc) in micro/nanofluidics is an important research area for the successful applications of micro/nanofluidics. One of the surface properties is the electroosmotic mobility. Current-monitoring method as illustrated in Fig. 1 [2] has been widely used for measurement of electroosmotic mobility  $\mu_{EO}$  ( $=L/Et_0$ ) in capillary electrophoresis and microfluidic chips, where  $E$  is the electric field,  $L$  the effective channel and  $t_0$  the elapsed time to completely replace 4X Tris-Borate-EDTA (TBE) buffer in the channel by 5X TBE. Most research work focused on theoretical modeling [3], extension to measurements of low  $\mu_{EO}$  [4] & low concentration of TBE buffer [5] or using electroneutral EOF marker [6]. However, to date there is no research on the systematic study of optimum Peclet numbers (Pe), a measure of the ratio of the rate of advection to the rate of diffusion, for accurate  $\mu_{EO}$  measurement of complex DNA buffers and solutions, especially those high-concentration buffers (5X TBE) frequently used in micro/nanofluidics. Pe is defined as  $L\mu_{EO}E/D$ , where  $D$  is the molecular diffusion constant. At low Pe, it is difficult to accurately determine  $t_0$  due to diffusion broadening, whereas at high Pe, it is easier. Therefore, a minimum Pe number exists for certain electrolyte to obtain accurate  $\mu_{EO}$ . In this work, we conducted experimental and theoretical analysis of electroosmotic flow of both simple (NaCl) and complex electrolytes (concentrated TBE) to study the Pe effect on the accurate measurements of electroosmotic mobility.

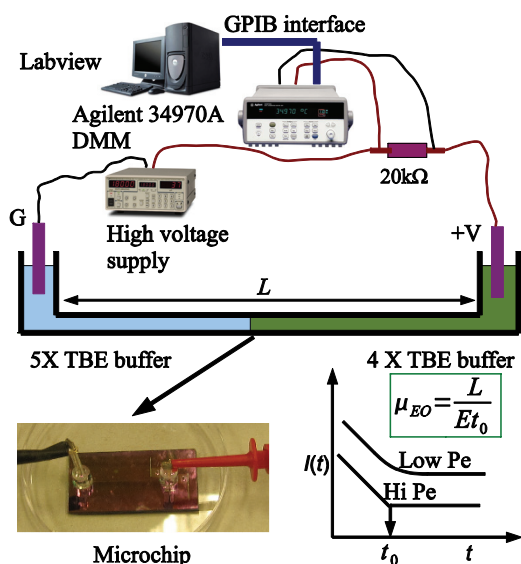


Figure 1. Experimental set-up for electroosmotic mobility measurement by current-monitoring method and a photograph of a packaged microfluidic chip.

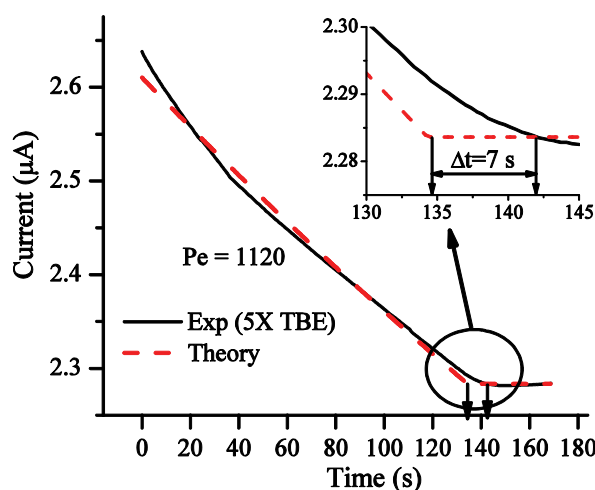


Figure 2. The solid curve is the measured current-time history at  $E = 93.3V/cm$  ( $V=140$  Volts) (5X TBE replaced by 4X TBE); Inset shows the time difference  $t = 7$  s compared with the theory.

## DEVICE FABRICATION AND EXPERIMENTS

A straight microfluidic chip with one simple microchannel ( $100 \mu m \times 5 \mu m \times 1.5$  mm) was fabricated on a 4-inch Si wafer with MEMS technology. The fabrication process was similar to our previous work at HKUST [7]. As show in Fig. 1, a high-voltage power supply (PS310, SRS, Inc., USA) was connected to the fabricated microchip. A 20 kΩ resistor

was used to monitor the electric current  $I(t)$  and recorded by a data acquisition system with a GPIB interface (Agilent 34970A, USA) and a Labview control program on a PC.

One typical current-time history under the applied voltage of 140 V with 5X TBE replaced by 4X TBE and time difference compared with the predicted  $I(t)$  from a simple 1D electroosmotic model with varying pressure gradient [3] was shown in Figure 2. The measurement error in the determination of the elapse time  $t_0$  ( $\Delta t$ ) can be obtained from the comparison between the experiments and 1D theory with the assumption that the diffusion constant is zero (inset of Fig. 2). Experiments with different solutions were conducted at different electric fields. In the fabricated microchannel, the channel height is larger than the Debye length by three orders of magnitude. Based on the assumption that electroosmotic velocity is linearly proportional to the applied electric field  $E$ , the electroosmotic mobility of 5X TBE and 20 mM NaCl are determined to be  $10,064 \pm 403.8 \mu\text{m}^2/\text{V}\cdot\text{s}$  and  $20,506 \pm 905.8 \mu\text{m}^2/\text{V}\cdot\text{s}$ , respectively as shown in Fig. 3. The results for 5 X TBE is consistent with Yasui's results ( $\sim 10,000 \mu\text{m}^2/\text{V}\cdot\text{s}$ ) [8].

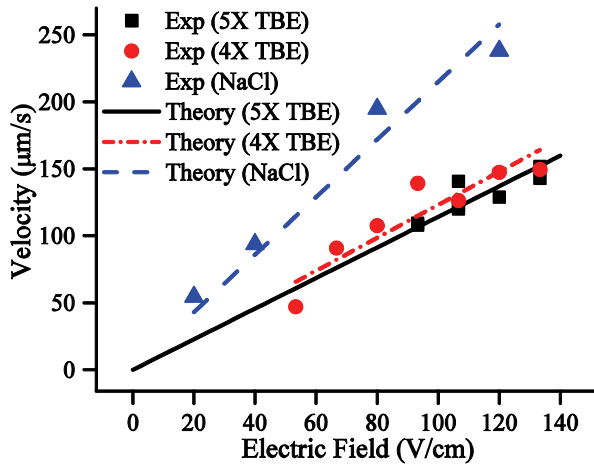


Figure 3. Electroosmotic velocity as a function of electric field; the solid, dash-dot and dash lines are for 5X TBE, 4X TBE, 20 mM NaCl, respectively.

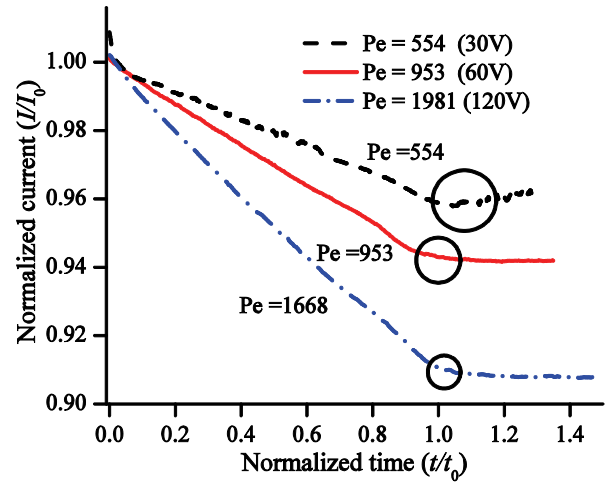


Figure 4. Normalized current-time history (experiment) for different Peclet numbers (20 mM NaCl, pH = 8.2), the circles highlight the transition.

## THEORETICAL ANALYSIS

In order to obtain accurate measurement results by using current-monitoring method, it is important to clearly identify the transition point, marked by a circle, in the current-time curve as shown in Fig. 2 to determine the elapsed time  $t_0$ . However, due to molecular diffusion at the interface between two different concentration regions, the transition point becomes unclear (see Fig. 2 and 4 with circles). In order to investigate the relationship between Peclet number and maximum measurement error, the following theoretical analysis is necessary:

The normalized maximum error ( $\Delta\mu_{EO}$ ), defined as  $e_{max}$ , of the measured electrophoretic mobility  $\mu_{EO}$  can be simply related to Peclet number. First,  $e_{max}$  can be related to the normalized maximum error of EOF velocity ( $\Delta v$ ) as follows:

$$e_{max} \equiv \frac{\Delta\mu_{EO}}{2\mu_{EO}} = \frac{\Delta v}{2v} = \frac{\frac{L}{t_0 - \Delta t} - \frac{L}{t_0 + \Delta t}}{2L/t_0} \approx \frac{\Delta t}{t_0} + O\left(\frac{\Delta t}{t_0}\right)^3 \quad (1)$$

where  $\Delta t$  is the maximum error of the elapsed time due to diffusion respectively;  $v$  is the average flow velocity without diffusion and  $L$  is the channel length. If we neglect the high-order terms in Equation (1) and employ the definition of Peclet number,  $e_{max}$  can be simply described as,

$$e_{max} \approx \frac{\Delta t v}{t_0 v} = \frac{2\sqrt{Dt_0}}{L} = 2\sqrt{\frac{1}{P_e}} \propto \frac{1}{\sqrt{P_e}} \quad (2)$$

Finally, we show that  $e_{max}$  is inversely proportion to the square root of Peclet number.

As  $Pe$  is defined as  $L\mu_{EO}E/D$ , increasing the channel length and applied electric field can reduce the maximum error. However, for long channel length, the time needed for one experiment would become very long. For the case of high electric field strength, the Joule heating effect becomes more significant and eventually introduces additional error. Further detailed error analysis will be needed to consider all the diffusion induced error, measurement time requirement and Joule heating effect.

## RESULTS AND DISCUSSION

In order to compare the experimental results with the theoretical predictions from Equation (2), all the experimental errors were estimated by the method as shown in Fig. 3. First, the experimental results of current-time history curve was fitted to the theoretical results [3]. Second, the maximum time difference  $\Delta t$  was determined by comparison of the experimental results and theoretical results as illustrated in Fig. 3. Then the maximum error can be estimated by Equation

(1). Because the theoretical model proposed in [3] is based on an ideal condition without diffusion, we can consider that the maximum error was mainly induced by the diffusion. Finally, we can get the experimental results for maximum error induced by diffusion. Fig. 5 is the plot of maximum error with the corresponding Peclet number and applied electric field for NaCl (20 mM) and 5X TBE buffer. The experimental results of Pe versus  $e_{max}$  show good agreement with our theoretical predictions for both 5X TBE and 20 mM NaCl solutions. For the same desired accuracy, the minimum Peclet number for simple NaCl solution is larger than complex 5X TBE buffer. This is mainly because the diffusion constant of NaCl is larger than the effective diffusion constant of 5X TBE buffer.

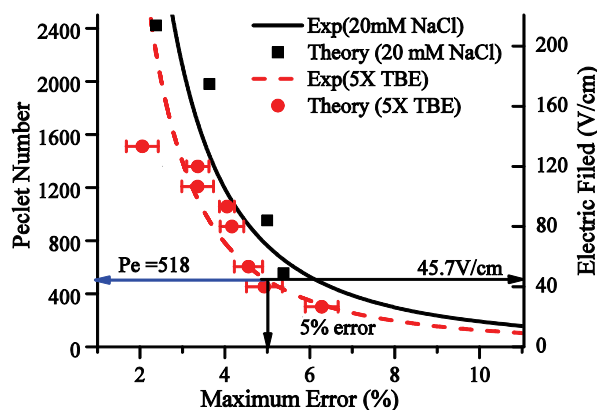


Figure 5. The average error in the experiments with corresponding Peclet number and electric filed for 5X TBE buffer and 20 mM NaCl.

For example, with maximum 5% error, the minimum Pe,  $Pe_{min}$ , should be large than 518 and 763 for 5X TBE buffer and NaCl (20 mM), respectively. This implies that the maximum measurement error primarily depends on Peclet number. Table 1 shows the minimum Peclet numbers for two fluids with desired accuracy. However, the proposed model can only be applied to the error source due to diffusion. If there are other dominant error sources such as Joule heating effect, more sophisticated model will be necessary.

Table 1. Minimum Peclet numbers for electroosmotic mobility measurement with different errors.

Max. error (%)	1%	3%	5%
$Pe_{min}$ for 5X TBE	$1.29 \times 10^4$	$1.44 \times 10^3$	518
$Pe_{min}$ for 20 mM NaCl	$1.91 \times 10^4$	$2.12 \times 10^3$	763

## CONCLUSION

In conclusion, with the synergy of experiments and theoretical analysis, we successfully determined the optimum Peclet numbers for the measurement electroosmotic mobility with controlled errors in current-monitoring method. The idea of optimum Peclet number can be applied to different types of complex biofluidics used in micro/nanofluidics.

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