Measuring Wall Shear Stress
Using Multilayer Nano-Particle Image Velocimetry

Haifeng Li\textsuperscript{1}, Minami Yoda\textsuperscript{2}

\textsuperscript{1}: G. W. Woodruff School of Mechanical Eng., Georgia Inst. of Tech., Atlanta, GA USA, haifeng.li@gatech.edu
\textsuperscript{2}: G. W. Woodruff School of Mechanical Eng., Georgia Inst. of Tech., Atlanta, GA USA, minami@gatech.edu

Abstract
Particle-image velocimetry (PIV) using evanescent-wave illumination has been recently used to study flows within about 400 nm of the wall. The exponential decay of the evanescent-wave intensity with wall-normal distance $z$ implies that the particle image intensity can be correlated with the $z$-position of the tracer. Multilayer nano-particle image velocimetry (MnPIV) exploits this correlation to divide the particles illuminated by the evanescent wave into distinct “sub-layers” based on their image intensity. These layers are processed using particle-tracking techniques to obtain the velocity components parallel to the wall at different $z$-locations within a few hundred nm of the wall, and hence wall shear stress.

We present here the application of MnPIV to incompressible, steady and fully-developed Poiseuille flow of monovalent electrolyte solutions at nearly neutral pH values through fused silica microchannels with nominal cross-sectional dimensions of 41 $\mu$m $\times$ 262 or 312 $\mu$m. In all cases, the Reynolds number is 0.3 or less, and the velocity profile over the near-wall region imaged in these studies is essentially linear.

After determining the intensity of tracers at a given $z$-distance from the wall using experimental calibrations and assuming that the particle image intensity decays in a fashion similar to the evanescent-wave intensity, near-wall particle distributions were obtained as a function of $z$ for monovalent electrolyte solutions at various pH and ionic strengths. The measured particle distributions are markedly nonuniform, with virtually no particles within 120 nm (more than a particle diameter) of the wall. Comparisons with results for alkali monovalent electrolyte solutions at the same ionic strength show that pH has a significant effect on the distribution, while ionic strength was observed to have a much smaller effect.

The tracers were evenly divided into three sub-layers based on the measured particle distribution. The temporally and spatially averaged velocity of each layer, determined by particle tracking, was placed at the average $z$-position sampled by the particles in that layer. The velocity data and velocity gradients obtained using MnPIV were compared with the exact solution for two-dimensional Poiseuille flow based on an independent measurement of the driving pressure gradient. The average deviation between the velocity gradient obtained with MnPIV and the exact solution is about 5%.

1. Introduction

Over the last decade, velocimetry techniques using particle tracers have been extended to studies of microflows, or flows with an overall dimension less than 500 $\mu$m. Much of this research has been motivated by the development of “Lab-on-a-Chip” or “micro-Total Analysis System” devices. Although velocimetry techniques such as hot-wire anemometry (HWA) and molecular tagging velocimetry (MTV), have also been used to study such flows (Sinton 2004; Breuer 2005), the most commonly used technique for measuring velocity fields in microfluidic devices is microscale PIV ($\mu$PIV) (Santiago et al. 1998). Unlike conventional PIV, which uses a laser light sheet or a scanned focused laser beam to image a “slice” of a flow seeded with particle tracers, $\mu$PIV uses volume illumination and relies instead upon the relatively small depth of the field of a high-magnification microscope objective to image a two-dimensional plane of a microscale flow seeded with colloidal particles. The thickness (dimension along the optical axis) of the region imaged by $\mu$PIV, quantified by the “depth of correlation” (Olsen and Adrian 2000), usually exceeds 2 $\mu$m.

Given the importance of surface (vs. bulk) effects at these small spatial scales, characterizing interfacial or near-wall transport is of interest in various applications, including determining whether the no-slip boundary condition is valid within a few hundred nanometers of the wall. The
µPIV studies with the best near-wall spatial resolution include the investigations of microscale Poiseuille flow performed by Tretheway and Meinhart (2002), who measured velocities within 900 nm of the wall (based on the size of their interrogation window) and Joseph and Tabeling (2005), who obtained velocities within 500 nm of the wall (based on the thickness of the region imaged). An alternative approach to obtaining near-wall PIV data is to use evanescent-wave (vs. volumetric) illumination (Zettner and Yoda 2003). When a beam of light is incident upon a refractive-index interface (such as that between glass and water) at an angle of incidence greater than the critical angle \(
abla_\theta \equiv \sin^{-1}(n_1 / n_2)\), where \(n_1\) and \(n_2\) are the refractive indices of the less dense and denser media, respectively, the light is totally internally reflected within the denser medium. An “evanescent wave,” with an intensity \(I\) that decays exponentially with distance normal to the interface \(z\), is generated in the less dense medium (such as water):

\[
\frac{I(z)}{I_0} = \exp \left( -\frac{z}{z_p} \right) \tag{1}
\]

Here, \(I_0\) is the intensity at the interface (i.e., \(z = 0\)) and \(z_p\) is the penetration depth, which is a function of the wavelength of the light \(\lambda\), the angle of incidence \(\theta \geq \theta_\epsilon\), and \(n_1\) and \(n_2\).

For visible light and a glass-water interface where \(n_1 = 1.33\) and \(n_2 \approx 1.5\), \(z_p\) is \(O(100 \text{ nm})\). The typical detection limits of most high-gain cameras restrict the region illuminated by the evanescent wave to less than about \(4z_p\), or within the first 500 nm next to the wall. Evanescent-wave illumination is therefore inherently limited to the near-wall region of microscale flows, resulting in less background noise compared with volumetrically illuminated images.

Evanescent-wave-based PIV, or nano-PIV (nPIV), using 100 nm–500 nm diameter fluorescent colloidal polystyrene spheres has been used to study steady electroosmotic flow within about 400 nm of fused silica microchannel walls (Sadr et al 2004) including measurements of the velocity deficit inside the electric double layer (Sadr et al 2006), near-wall Brownian diffusion (Choi et al. 2007), and slip over hydrophilic and hydrophobic surfaces (Huang et al 2006). Recently, evanescent wave-based velocimetry has been extended to semiconductor nanocrystal, or quantum dot, tracers with an effective diameter of about 10 nm (Pouya et al. 2005, 2008).

Eq. (1) suggests that particles illuminated by evanescent waves that are closer to the wall should have brighter images. It should therefore be possible to correlate the image intensity of each particle with the distance between that particle center and the wall, \(z\). Given variations in image intensity between particles at the same \(z\) due to particle polydispersity, among other factors (cf. Sec. 2.2), we have developed an extension of nPIV, multilayer nPIV (MnPIV) (Li et al. 2006), where the particles in a typical nPIV image are distributed instead among a few sub-layers within the region interrogated by the evanescent wave based upon their image intensities. The sub-images corresponding to these layers can then be processed using standard techniques to determine velocities at different \(z\) values within 500 nm of the wall.

Multilayer nPIV has been used to study two-dimensional Poiseuille flow of water and alkali (pH~9.1) monovalent electrolyte solutions (Li and Yoda 2008). In all cases, the near-wall particle distribution was found to be strongly non-uniform, with almost no particles within 100–150 nm of the wall. Nevertheless, the MnPIV results, after correcting for this non-uniform distribution, gave estimates of near-wall velocity gradient (and hence wall shear stress) within 5% on average of the values predicted by the analytical solution. In this work, we extend these studies to monovalent electrolyte solutions at nearly neutral pH (7.5–7.7) to determine how the pH and ionic strength of the working fluid affect near-wall particle distributions.

Section 2 details our experimental studies and image processing of the incompressible, steady, fully-developed and creeping Poiseuille flow of aqueous ammonium bicarbonate (\(\text{NH}_4\text{HCO}_3\)) solutions at salt molar concentrations \(C = 2\text{ mM}\) and 10 mM driven through 41 µm deep microchannels at Reynolds numbers of 0.3 or less. Section 3 describes the particle distribution.
and MnPIV results and compares them with both the analytical solution for Poiseuille flow between two parallel plates and our previous MnPIV results for water and sodium tetraborate (Na$_2$B$_4$O$_7$) solutions at the same ionic strengths.

2. Experimental Details

2.1 Poiseuille flow

Steady Poiseuille flow was studied in microchannels of depth (z-dimension) 41 µm and width at the channel half-depth of 262 µm or 312 µm, giving a channel hydraulic diameters $D_h = 71$ µm and 73 µm, respectively (Figure 1). The fused silica channels were wet-etched in a substrate, giving a nominally trapezoidal cross-section, and sealed with a “lid” using a high-temperature bonding process. As shown, the region imaged is 1.7 cm, or more than 200$D_h$, downstream of the bend to ensure fully-developed flow. The driving pressure gradient $dp/dx$, here the pressure difference measured between the upstream and downstream reservoirs divided by the channel length of about 3.6 cm, was generated hydrostatically using an adjustable-height tank; $dp/dx$ varied by less than 1% during a single experiment. We present here results for $dp/dx = 0.4$–1.0 Bar/m, corresponding to Reynolds numbers $Re$ based on average speed and $D_h$ of 0.1 to 0.3.

![Fig. 1](image)

Fig. 1 Cross-section [left] and top views [right] of the fused silica microchannels. “IR” refers to the imaged region. The flow is out of the page and downwards in the cross-section and top views, respectively. All dimensions are given in µm in the cross-section.

The “true” velocity profile in this flow was defined to be that for the exact solution for Poiseuille flow between two infinite parallel plates with a z-spacing of $H = 41$ µm:

$$u(z) = \frac{H^2}{2\mu} \frac{dp}{dx} \left[ \frac{z}{H} \left(1 - \frac{z}{H}\right) \right]$$  \hspace{1cm} (2)

The velocity profile of Eq. (2) was virtually identical to the analytical solution in the center of the duct for Poiseuille flow in a rectangular duct (Panton 2005, for example); note that the channel cross-section in all cases has an aspect ratio exceeding 6. The fluid viscosity $\mu$ was assumed in all
cases to be that of water at the temperature of the exit reservoir measured by a type K thermocouple.

Given that the $z$-extent of the region interrogated by MnPIV is 400 nm, less than 1% of the channel depth $H$, the near-wall flow studied here has a velocity profile that is essentially linear. These velocity profiles were characterized in terms of their shear rate $G$, which was determined by linear regression of the velocity profile $u(z)$ (cf. Eq. 2) for $z \leq 400$ nm.

MnPIV experiments were performed with two different working fluids, namely aqueous ammonium bicarbonate (NH$_4$HCO$_3$) solutions at molar concentrations $C = 2$ mM and 20 mM at pH 7.5 and 7.7, respectively, in the $D_h = 71 \mu$m channel. Particle distributions were also measured for a $C = 10$ mM sodium tetraborate (Na$_2$B$_4$O$_7$) solution at pH 9.1 in the $D_h = 73 \mu$m channel. Sodium tetraborate and ammonium carbonate both dissociate to give monovalent ionic species as follows:

$$Na_2B_4O_7 + 7 H_2O \rightleftharpoons 2 Na^+ + 2 B(OH)_3 + 2 B(OH)_4^-$$

$$NH_4HCO_3 \rightleftharpoons NH_4^+ + HCO_3^-$$

These concentrations were chosen so that the ionic strengths $I \equiv \sum_i (c_i z_i^2)/2$ (where $c_i$ and $z_i$ are the molar concentration and valence of the $i$th electrolyte, respectively) of these monovalent electrolyte solutions matched those of the $C = 1$ mM and 10 mM monovalent Na$_2$B$_4$O$_7$ solutions studied in Yoda and Li (2008) (Table I). The working fluids will be described in the rest of this paper in terms of their ionic strengths $I$.

**Table I** Salt molar concentrations $C$ and corresponding ionic strength $I$ for the ammonium bicarbonate and sodium tetraborate solutions studied here and in Yoda and Li (2008).

<table>
<thead>
<tr>
<th>Working fluid</th>
<th>I [mM]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C = 2$ mM NH$_4$HCO$_3$</td>
<td>2</td>
</tr>
<tr>
<td>$C = 1$ mM Na$_2$B$_4$O$_7$</td>
<td>2</td>
</tr>
<tr>
<td>$C = 20$ mM NH$_4$HCO$_3$</td>
<td>20</td>
</tr>
<tr>
<td>$C = 10$ mM Na$_2$B$_4$O$_7$</td>
<td>20</td>
</tr>
</tbody>
</table>

Ammonium bicarbonate salt (ACS reagent grade, Acros Organics) was dissolved in 25 mL Nanopure water (ACS reagent grade with a quoted resistivity >18 MΩ·cm, Ricca Chemical Company). The pH values of the NH$_4$HCO$_3$ solutions, which are weak buffers, were measured by a pH meter (Oakton pH-11) at 19 °C (the ambient temperature). A small amount of fluorescent polystyrene spheres (Invitrogen FluoSpheres f-8888) of radius $a = 50$ nm (standard deviation in radius of 6%), supplied by the manufacturer as an aqueous solution at a volume fraction of 2%, were added to the salt solutions to give a nominal volume fraction of $2 \times 10^{-5}$, or a number density $c = 4.4 \times 10^{16}$ m$^{-3}$.

The microchannel is mounted on the stage of an inverted epi-fluorescent microscope (Leica DMIRE2). The flow is illuminated by evanescent waves generated using prism coupling of a $\lambda = 488$ nm beam from an argon-ion laser (Coherent Innova 90) at an output power of 150 mW. The angle of incidence $\theta \approx 70^\circ$, corresponding to $z_p = 113 \pm 3$ nm, based on the refractive index of the fused silica $n_2 = 1.46$. The fluorescent tracers are imaged through a dichroic filter cube that transmits on the fluorescence (wavelengths $\lambda \geq 515$ nm) by a 63×, 0.7 numerical aperture objective (Leica PL Fluotar L) and a $0.5\times$ camera adaptor onto a CCD camera with on-chip multiplication gain (Photometrics Cascade 650). In all cases, the region imaged in these experiments is adjacent to the unetched surface of the lid sealing the channel, which is the smoothest channel wall with a mean surface roughness according to the manufacturer (Esco Products, Inc., Oak Ridge, NJ) of 3 nm (Fig. 1).
Pairs of 653 (streamwise dimension) × 100 (cross-stream dimension) pixel images, corresponding to physical dimensions of 154 µm × 24 µm, were acquired using an acousto-optic modulator (IntraAction AOM-40) driven by a function generator (Wavetek Datron 195) to create two particle exposures, each of 0.8 ms, separated by a time interval \( \Delta t = 1.5 \) ms. The temporal spacing between successive image pairs varied from about 20 ms to 220 ms because of limitations in transferring images from the camera to the PC hard drive. These variations in temporal spacing between image pairs should not affect the results for this steady flow. In all cases, the total acquisition time was 53±1 s for a sequence of 300 image pairs. Two such sequences were recorded during each experimental run.

2.2 Image Processing

After compensating for camera nonlinearity, individual particle images were identified in each image using the approach of Crocker and Grier (1996). Flocculated particles were eliminated by filtering out the particle images with eccentricities exceeding 10%. The particle image intensity \( J_p \) was defined as the maximum grayscale value in each particle image.

Several previous studies (Chew et al. 1979; Prieve and Walz 1993; McKee et al. 2005; Li and Yoda 2008, among others) have concluded that the image intensity of colloidal particles illuminated by evanescent waves decays exponentially with \( z \), and that the length scale of this exponential decay is (within experimental error) \( z_p \), the penetration depth of the illumination. We therefore modeled the particle image intensity \( J_p = J_p^0 \exp\{-h/z_p\} \), where \( h \) is the distance between the particle edge and the wall (\( h = z - a \)). The image intensity of particles attached to the surface (\( h = 0 \)) \( J_p^0 \) was determined experimentally from images of stationary \( a = 50 \) nm tracers electrostatically attached to the wall by \( \text{Ca}^{2+} \) and illuminated and imaged with the same setup used for the MnPIV experiments. The standard deviation in the image intensity of the stationary tracers was about 9%, presumably due to variations in the amount of fluorophore between particles, particle polydispersity and camera noise. \( J_p^0 \) was taken to be the maximum grayscale value among about 7000 stationary particle images; about 300 (~4%) of the particle images actually had this maximum grayscale value.

The model of particle image intensity then gives the \( z \)-position of each particle as:

\[
z = z_p \ln(J_p^0 / J_p) + a
\]

We estimate, based on the uncertainty in \( J_p^0 \) and in our experimental estimates of \( z_p \), that the 95% confidence intervals for estimating the \( z \)-position of each particle is 23 nm or less. Further details of the experimental procedures and image processing are given in Li and Yoda (2008).

3. Results

3.1 Near-Wall Particle Distributions

Figure 6 shows the particle number density \( c(z) \) for \( I = 2 \) mM (●) and 20 mM (◆) \( \text{NH}_4\text{HCO}_3 \) solutions, at pH 7.5 and 7.7, respectively, and \( I = 20 \) mM \( \text{Na}_2\text{B}_4\text{O}_7 \) solution (▲) at pH 9.1. As shown in Table I, the neutral and alkali monovalent electrolyte solutions have the same ionic strength. In all cases, each curve is obtained from more than \( 8 \times 10^4 \) particle images.
Fig. 2  Profile of particle density $c$ over $z$, the distance between the particle center and the wall, for $I = 2 \text{ mM} (\bullet)$ and $20 \text{ mM} (\bigstar) \text{NH}_4\text{HCO}_3$ solutions and $I = 20 \text{ mM} \text{Na}_2\text{B}_4\text{O}_7 (\bigtriangleup)$ solution.  

The results demonstrate that the tracer distribution within 400 nm of the wall is strongly non-uniform, with virtually no particles within 120 nm (i.e., more than a particle diameter) of the wall, presumably due to the electrostatic repulsion between the fused silica surface (which should be negatively charged at this pH) and the carboxylate-modified polystyrene particles, which should also have a negative surface charge.  The particle density reaches a maximum just above $z = 150$ nm, then decays to a roughly uniform value of $8 \times 10^{16} \text{ m}^{-3}$ for $z > 300$ nm.  More importantly, these data show that the near-wall particle distribution varies significantly with the pH of the solution.  Given that the $pK_a$ of the surface silanol groups exposed on the fused silica wall is 6.5 (Iler 1979), the wall surface charge will be less negative (i.e., have a smaller magnitude) at pH 7.5–7.7* than at pH 9.1, reducing the electrostatic repulsion between the tracers and the wall.  These variations in solution pH should have less effect on the surface charge of the tracers, since the $pK_a$ of carboxylate-modified polystyrene is typically less than 4.5.  Ionic strength appears to have a much smaller effect; this observation is not surprising, given that an order of magnitude change in $I$ from 2 mM to 20 mM in the NH$_4$HCO$_3$ solutions will only change the Debye screening length solutions which characterizes the extent of the electric double layer, or layer of counterions that screen the charged surface, from 7 nm to 2 nm, respectively (Bird et al. 2002).

These particle distribution data were then used to determine the boundaries of three sub-layers, each containing roughly one-third of the particles, for subsequent MnPIV processing:  (I) $z = [50 \text{ nm}: 200 \text{ nm}]$; (II) $z = [200 \text{ nm}: 300 \text{ nm}]$; and (III) $z = [300 \text{ nm}: \sim 410 \text{ nm}]$, as denoted by the dashed lines in Figure 2.  The upper boundary of the entire imaged region, $z_{\text{III}} = 410$ nm, was taken to be the $z$-location of the particle with the lowest image intensity detectable above the background noise level of the camera.  Figure 3 shows a typical image of $a = 50$ nm particles

* By definition, at a pH of 6.5 ($= pK_a$), only half of the surface silanol groups will have become de-protonated and hence negatively charged
illuminated by evanescent waves (inverted for clarity) [left] divided into three sub-images, or sub-layers [right] for 2 mM NH$_4$HCO$_3$ at a shear rate $G = 2400 \text{ s}^{-1}$.

Fig. 3 A typical inverted image (exp. 0.5 ms) of fluorescent particles [left] divided into three sub-images, each containing about 1/3 of the particles [right] for the Poiseuille flow of $I = 2 \text{ mM NH}_4\text{HCO}_3$ at $G = 2400 \text{ s}^{-1}$.

3.2. MnPIV Results

To minimize the effects of the non-uniform evanescent-wave illumination (Sadr et al. 2007), particle-tracking velocimetry (PTV) based on the approach of Baek and Lee (1996) was used (vs. cross-correlation methods) to determine individual displacement, and hence velocity, vectors. The velocity data of each sub-layer were then temporally and spatially averaged over 600 image pairs from three independent experimental runs to obtain $u_M$, the average tracer velocity in that layer. Displacements of particles moving between sub-layers within the image pair were excluded from this average.

The $z$-position of this particle-based velocity, $\langle \tilde{z} \rangle$, was determined from the expected particle velocity for this flow $\tilde{u}_p$ for each sub-layer:

$$\tilde{u}_p = \frac{\int_{z_L}^{z_U} c(z)u(z)dz}{\int_{z_L}^{z_U} c(z)dz} \quad (4)$$

where $c(z)$ denotes the experimentally particle distribution from Figure 2, $u(z)$ is the “true” velocity profile given in Equation 2, and $z_L$ and $z_U$ represent the lower and upper $z$-boundaries, respectively of the layer. Given the lack of particles within a diameter of the wall, no attempt was made to correct these near-wall velocities for particle rotation effects (Goldman et al. 1967). Finally, $\langle \tilde{z} \rangle$ was interpolated from Equation 2 where $u(\langle \tilde{z} \rangle) = \tilde{u}_p$. As expected, $\langle \tilde{z} \rangle > z_c$, where the geometric center of the layer $z_c \equiv (z_L + z_U)/2$, in the layer closest to the wall because of the lack of particles at $z \leq 2a$. In the layers farther from the wall, however, $\langle \tilde{z} \rangle = z_c$.

Figure 4 gives a plot of near-wall velocities as a function of distance from the wall. The Figure compares the MnPIV results $u_M$ plotted as a function of $\langle \tilde{z} \rangle$ for the Poiseuille flows of (a) $I = 2 \text{ mM NH}_4\text{HCO}_3$ driven by pressure gradients corresponding to shear rates $G = 990 \text{ s}^{-1}$ (▲), 1700 s$^{-1}$ (●) and 2400 s$^{-1}$ (◆) and (b) $I = 20 \text{ mM NH}_4\text{HCO}_3$ at $G = 960 \text{ s}^{-1}$ (▲), 1700 s$^{-1}$ (●) and 2300 s$^{-1}$ (◆). The error bars represent 95% confidence intervals. The MnPIV results are compared with the appropriate “true” velocity profile given by $U = Gz$ (solid line). The underestimation of the velocities in layer I for the $I = 20 \text{ mM}$ case may be due to the marked peak for this case near the wall (cf. Figure 2), and will be the subject of further investigation. Note that (asymmetric) Brownian diffusion-induced bias—which, according to our previous analyses, should
give an overestimation in the velocity in layer I—should be negligible in these studies (Sadr et al. 2007).

Table II compares the shear rates $G_3$ or velocity gradients $\partial u / \partial z$ obtained by a linear regression of the MnPIV results $(u_M, \langle \bar{z} \rangle)$ for all three layers and the origin $(0,0)$ with $G$ for both cases. The magnitude of the errors range from 1 to 10%, and average about 5% for both $I = 2$ mM and 20 mM ammonium bicarbonate solutions. These errors are comparable to those reported in Li and Yoda (2008) for $I = 2$ mM, 20 mM and 40 mM sodium tetraborate solutions and Nanopure water.

![Graphs showing velocity profiles](image)

**Fig. 4** Velocity profiles for the MnPIV results $u_M$ in terms of $\langle \bar{z} \rangle$, the $z$-position of this result based on the particle distributions given in Figure 3 and compared with the velocity profile $U = Gz$ (solid lines) for (a) $I = 2$ mM NH$_4$HCO$_3$ driven by pressure gradients corresponding to shear rates $G = 990 \text{ s}^{-1}$ (▲), 1700 $\text{s}^{-1}$ (●) and 2400 $\text{s}^{-1}$ (●) and (b) $I = 20$ mM NH$_4$HCO$_3$ at $G = 960 \text{ s}^{-1}$ (▲), 1700 $\text{s}^{-1}$ (●) and 2300 $\text{s}^{-1}$ (●). The error bars represent 95% confidence intervals.

**Table II** Comparison of shear rates obtained from MnPIV results with those predicted by Equation 2.

<table>
<thead>
<tr>
<th></th>
<th>$I = 2$ mM</th>
<th></th>
<th>$I = 20$ mM</th>
</tr>
</thead>
<tbody>
<tr>
<td>$G$ (s$^{-1}$)</td>
<td>$G_3$ (s$^{-1}$)</td>
<td>$\frac{</td>
<td>G_3 - G</td>
</tr>
<tr>
<td>990</td>
<td>1080</td>
<td>9</td>
<td>960</td>
</tr>
<tr>
<td>1700</td>
<td>1820</td>
<td>4</td>
<td>1700</td>
</tr>
<tr>
<td>2400</td>
<td>2460</td>
<td>3</td>
<td>2300</td>
</tr>
</tbody>
</table>
4. Summary

Multilayer nano-particle image velocimetry (MnPIV), which exploits the exponential decay of evanescent-wave illumination to determine the wall-normal position $z$ of near-wall particles, and hence their spatial distribution in $z$, was used to determine how varying the ionic strength and pH of dilute monovalent electrolyte solutions affects the near-wall particle distribution. The study builds upon the recent experimental results reported in Li and Yoda (2008).

MnPIV studies were carried out on the creeping (Reynolds numbers of 0.3 or less) fully-developed two-dimensional Poiseuille flow through fused silica microchannels with hydraulic diameters of about 70 $\mu$m. The experimentally measured particle distributions for the same negatively charged fluorescent 100 nm diameter polystyrene particles suspended in monovalent electrolyte solutions at ionic strengths of 2 mM and 20 mM and pH values of about 7.6 and 9.1 show that the pH of the fluid has much more effect on the particle distribution than the ionic strength. This result is hardly surprising given that the pH, by affecting the dissociation equilibrium of the silanol groups on the surface of the fused silica walls and hence the particle-wall electric potential, while the ionic strength $I$ indirectly affects this potential by changing the Debye length, which scales as $I^{-1/2}$.

The velocity gradients obtained from the MnPIV data, after correcting for this non-uniform particle distribution, are at worst within 10%, and on average within 5%, of the predicted values. These discrepancies are comparable to our previous experimental results. These studies illustrate some of the challenges in obtaining accurate near-wall tracer-based velocity data, and in interpreting such measurements.

References

Breuer KS 2005 Microscale diagnostic techniques. Springer Heidelberg
Choi CK, Margraves CH, Kihm KD 2007 Examination of near-wall hindered Brownian diffusion of nanoparticles: Experimental comparison to theories by Brenner (1961) and Goldman et al. (1967). Phys Fluids 19:103305/1–10
Joseph P, Tabeling P 2005 Direct measurement of the apparent slip length. Phys Rev E 71:035303(R)/1–4
Li HF, Yoda M 2008 Multilayer nano-particle image velocimetry (MnPIV) in microscale Poiseuille flows. To appear in Meas Sci Technol
Olsen MG, Adrian RJ 2000 Out-of-focus effects on particle image visibility and correlation in microscopic particle image velocimetry. Exp Fluids 7:S166–S174
Prieve DC, Walz JY 1993 Scattering of an evanescent surface-wave by a microscopic dielectric sphere. Appl Optics 32:1629–1641
Sinton D 2004 Microscale flow visualization. Microfluid Nanofluid 1: 2–21
Tretheway DC, Meinhart CD 2002 Apparent fluid slip at hydrophobic microchannel walls. Phys Fluids 14:L9–L12
Zettner CM, Yoda M 2003 Particle velocity field measurements in a near-wall flow using evanescent wave illumination. Exp Fluids 34:115–121