

DIRECT MEASUREMENT AND SIMULATION OF APPARENT SLIP VELOCITIES IN SUB-MICRON-SCALE FLOWS

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Summary The possible existence of slip of liquids in close proximity to a smooth surface is studied experimentally and numerically via the dynamics of small particles suspended in a shear flow. Sub-micron fluorescent particles suspended in water and imaged using Total Internal Reflection Fluorescence Microscopy (TIRFM) and a PTV algorithm. The measurements are in excellent agreement with Monte Carlo simulations of particle dynamics, and show that the observed “apparent slip velocity” is a direct consequence of the small, but finite, measurement volume, and that slip, if present, is minimal at the low shear rates tested ($< 2500 \text{ s}^{-1}$). Issues associated with the experimental and simulation techniques and the interpretation of results are also discussed.

The validation of the no-slip boundary condition on both hydrophilic and hydrophobic surfaces has been a subject of intense recent interest [1-3] with results predicting “apparent slip” lengths ranging from nanometers to microns. In related research, the motion of submicron particles and macromolecules as they approach the solid surface is also a matter of both scientific and technological interest in microfluidic systems [4]. In this paper, we report on complementary experiments and simulations of particles flowing in a microchannel as they move within 200 nm of a smooth surface that has been treated to be either hydrophilic or hydrophobic.

The experiments use Total Internal Reflection Fluorescence Microscopy (TIRFM) and Particle Tracking Velocimetry (PTV). A pair of 532-nm, 5-nsec laser pulses are directed through a high numerical aperture microscope objective at an angle that creates total internal reflection at the glass-water interface (figure 1), thus illuminating the near-wall region with the evanescent light field. Test channels were fabricated using PDMS molding techniques and bounded onto a glass wafer, (RMS surface roughness less than 4 nm). Image pairs of particles were captured using an intensified CCD camera and analyzed using custom PTV algorithms [5].

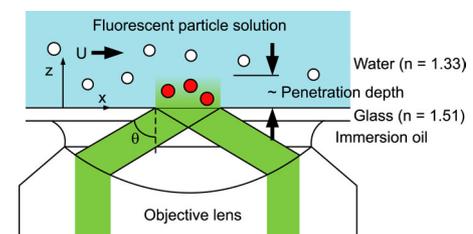


Figure 1. Schematic of objective-based TIRFM setup.

The experimental results were compared with a Monte Carlo simulation of particle Brownian motion in a shear flow. 10,000 particles were uniformly distributed in a shear layer within the evanescent wave penetration depth. At each time step, Δt , the particle was moved at the local velocity (using an assumed velocity profile) and subjected to Brownian motion, sampled from a normal distribution with a zero mean and a standard deviation of $(2D\Delta t)^{1/2}$, where D is the diffusion constant. The diffusion constant was modified to account for the presence of the wall using corrections based on analytical solutions to the problem of confined diffusion both normal and parallel to the surface [6,7]. To prevent particles from moving through the wall, a specular reflection boundary condition was imposed when particles come into contact with the wall (this is not strictly accurate and will be improved in future simulations, however the solution is not very sensitive to this feature of the technique). After many thousand timesteps, particles that remained in an “observation depth” (defined in conjunction with the experiment and based on minimum image intensity threshold) were counted and particle displacements from their initial positions were calculated to obtain displacement, and consequently apparent velocity distributions, similar to those obtained from the physical experiments. It is important to realize that the distributions are sensitive to both the choice of the observation depth and the character of the slip/no-slip boundary condition at the solid surface.

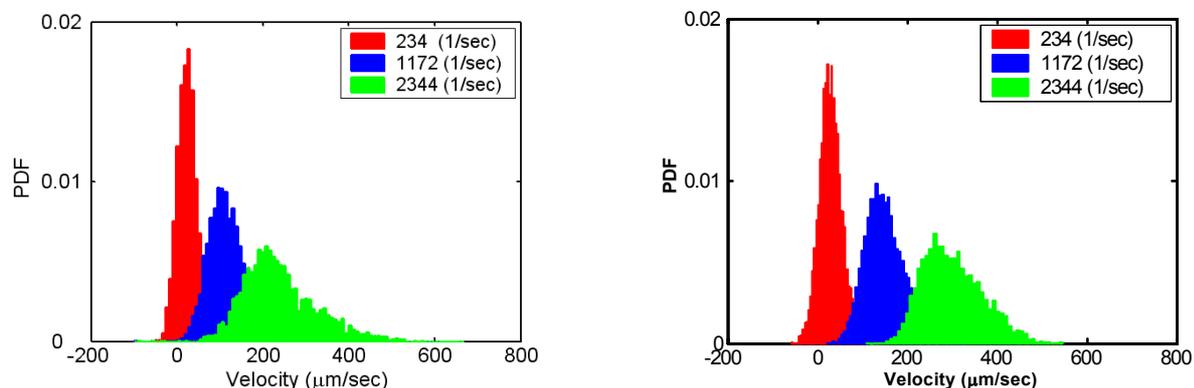


Figure 2. Distributions of velocity at three shear rates. The left frame shows the experimental results while the right frame shows the corresponding result from the Monte Carlo simulation (using an assumed observation depth of 175 nm).

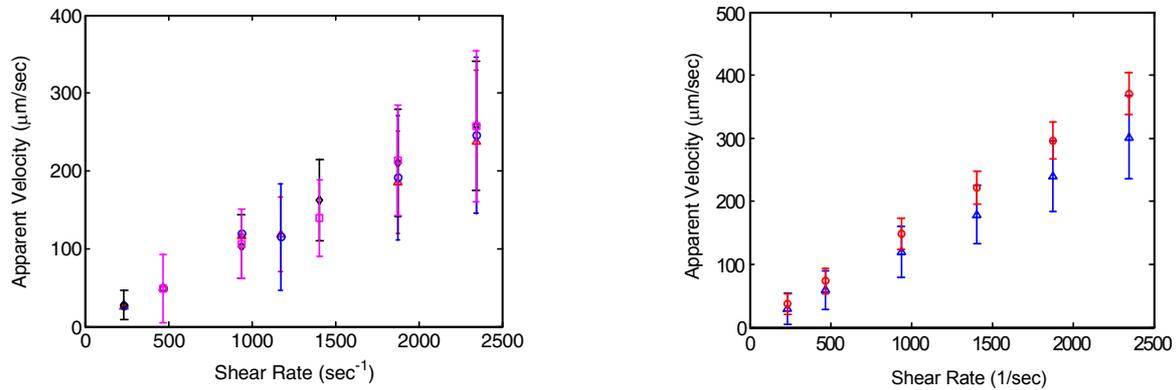


Figure 3. Apparent velocity vs. shear rate. The left frame shows the experimental results (hydrophilic: 200-nm particles – red; 300-nm particles – black / hydrophobic: 200-nm particles – blue; 300-nm particles – pink) while the right frame shows the Monte Carlo simulation (200-nm particles – blue; 300-nm particles – red) at observation depth = 175 nm.

Figure 2 shows an example of the distribution of streamwise apparent velocities obtained from (a) physical experiment and (b) simulation. We observe that the peak of the distribution increases with increasing shear rate, as do both the distribution width (standard deviation) and its skewness. Such observation merely reflects the fact that tracking particles with a finite interrogation volume samples particles traveling at several local velocities all of which contribute to the apparent velocity. This also explains the increasing width and skewness of the distributions as the shear rate increases, although the high skewness is primarily due to the sharp reduction in the diffusion coefficient when the particle is very close to the wall. Figure 3 shows the variation of the mean velocities and their standard deviations (denoted as error bars) as a function of shear rate. The velocities appear to fall on a straight line through the origin and that there is no clear difference between hydrophilic and hydrophobic surfaces at these (low) shear rates. The slope of the line suggests that the slip length, if it exists, has a magnitude of less than 20 nm – consistent with some of the recent measurements [1], but in contrast to others [2,3]. One puzzling observation is that there appears little difference between the streamwise velocities obtained using 200- and 300-nm particles, while numerical simulation suggests that a difference should exist if a uniform observation depth is used. The shape of the distributions from both the numerical simulation and experimental measurements are quite sensitive to the selected observation depth (figure 4). Consequently, the similarity between the 200- and 300-nm particle experimental data is likely due to the differences in selected observation depths, and their overlap is merely coincidental. Experiments are currently underway to obtain calibrated particle intensity profiles at different observation depths, which will enable direct measurement of the three-dimensional motion of the particle and the observation depth and thus resolve this issue.

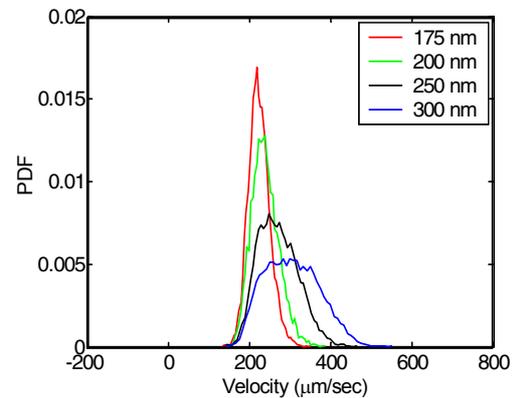


Figure 4. Simulated velocity distributions of 300-nm particles at a shear rate of 1400 sec^{-1} with four different observation depths.

The current results shed light on the dynamics of small particles in microfluidic systems and reinforce measurements that suggest that slip, if present, is small at low shear rates. Furthermore, we conclude that at the microscale, estimations of fluid velocity from observed particle motions near a solid surface should be treated with care. Experiments at higher shear rates and using more accurate (three-dimensional) measurements, are currently underway as well as more extensive and refined simulations. These will be reported upon at the ICTAM meeting.

References

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