AN ACCURATE VELOCITY PROFILE MEASUREMENT SYSTEM FOR MICROFLUIDICS : A DIRECT MEASUREMENT OF THE SLIP LENGTH.

Pierre Joseph, Patrick Tabeling

MMN, Ecole Supérieure de Physique et Chimie Industrielle de Paris, CNRS

10 rue Vauquelin, 75231 Paris, France

Summary We describe an accurate method to measure velocity profiles inside microchannels, using particle image velocimetry combined with a nano-positioning system. The experimental setup is used to measure the slip length for water flowing along an hydrophilic surface, pyrex glass, and an hydrophobic one, a monolayer of octadecyltrichlorosilane (OTS) over an atomically flat silicon substrate. In the pyrex case, we achieve an unprecedented accuracy (±100nm) for a direct measurement of the slip length; this length is found to be essentially zero. For silicon surfaces functionalized with OTS, the accuracy is lower. One obtains 200±300nm for the slip length in this particular case.

INTRODUCTION

In classical textbooks, it is considered that liquids do not slip on solid surfaces. This provides a fundamental condition in fluid mechanics, allowing for detailed calculations of velocity profiles and flow structures. The physical justification bears on the assumption that attractive Van der Waals forces tend to link fluid atomic layers to the solid, preventing slip to occur. More generally speaking, this condition has been confirmed by an overwhelming abundance of experimental measurements, performed in ordinary fluid systems. In contrast with this picture, recent experiments have shown that simple liquids significantly slip on atomically smooth solid surfaces and, consequently, the no-slip condition should be replaced by a more general relation. On usually adopts the following form :

$$v = b\left(\frac{\partial v}{\partial z}\right)$$

in which *b* is the extrapolation or slip length, *z* is the normal (inwards to the fluid). Measurements of *b* have been performed in various situations, for a variety of solid surfaces, and several fluids (Ref [1], [2], [3]). Results indicate the slip length is on the order of micrometers, or fractions of micrometers, i.e much larger than typical intermolecular scales. There is no clear understanding, at the moment, for this set of observations. A possibility suggested by Ref [4], is that a gaseous layer nucleates at the interface between the fluid and the solid, favouring slippage. This proposal remains to be investigated experimentally.

The objective of this paper is to make progress on the measurement of slip lengths, by developing a direct method of determination of the velocity (using PIV), in thin microchannels. The technique we present here allows, with unprecedented accuracy (±100 nm), to measure the slip length of water flowing over glass; the same technique is applied for atomically smooth silicon substrates, functionalized with OTS.

EXPERIMENTAL SETUP AND MEASUREMENT METHOD

A general scheme of the experiment is shown on figure 1 :

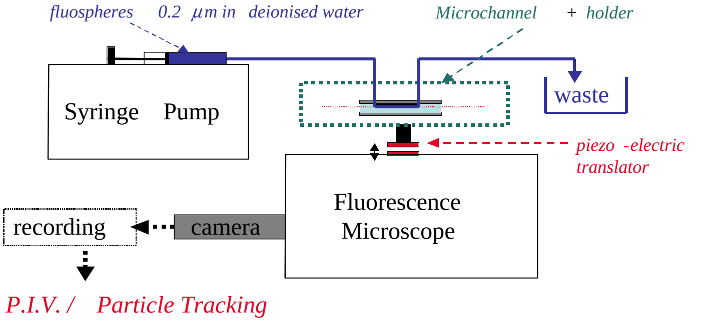

Figure 1 : Schematic view of the experimental setup.

Rectangular microchannels used in this experiment are 15µm thick, 200µm wide, and 2cm long. The stationary flow-rate (25nL per minute) is controlled by a syringe pump, the corresponding shear rate, at the wall, being $50s^{-1}$. The working solution is deionized water seeded with a 200nm-diameter fluorescent polystyrene beads. The lower surface of the channel is made of glass or atomically flat silicon, chemically modified by self-assembled-monolayer deposition of

a 2.3nm thick octadecyl-trichlorosilane (OTS). In the first case, water wets the surface, while in the second case, one gets a hydrophobic surface, showing a contact angle 95°, with an hysteresis of 10°.
Observation is made with an epifluorescent microscope (emission filter λ=515nm), a 100x oil immersion objective (index of refraction n=1.515), with a numerical aperture NA=1.3. The depth of field is then 460nm. In such conditions, one may image a thin layer of fluid, within the channel. In order to have a few beads in this volume, the volumetric fraction of the suspension is fixed to 2.10^{-5}.
The objective is mounted on a piezo-electric nano-positioner (20nm precision), which allows an accurate control of the fluid layer being imaged. A typical experiment consists of recording images with a video camera while scanning different z-positions inside the channel, in order to determine the entire velocity profile. Velocity is determined by PIV technique. For a reduction of random noise induced by brownian motion, measurements are typically obtained after averaging over 25 images.
In order to obtain an accurate determination of the wall position (with respect to the fluid), we measure the intensity emitted by stuck particles, for various positions of the objective (Figure 4b.). The experimental curve is then fitted with a Lorentzian, and the maximum is eventually determined, with an accuracy on the order of ±50nm.

RESULTS

A typical velocity profile obtained with a glass surface, in a 13µm thick microchannel, is shown on figure 4.

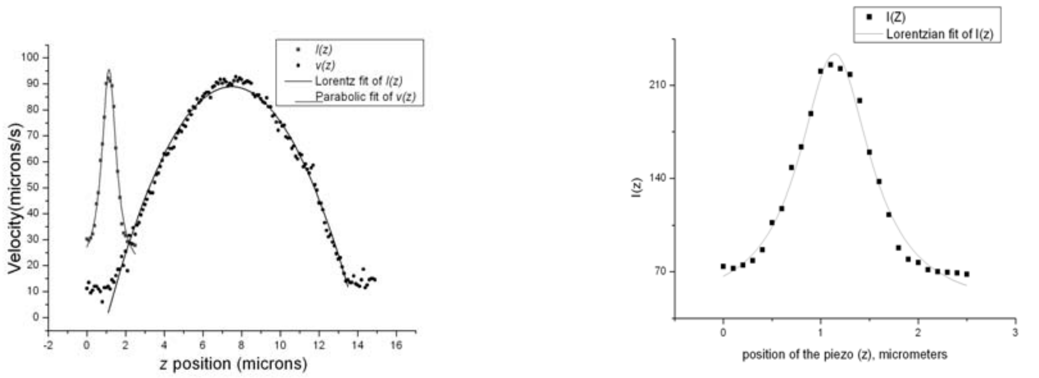

Figure 4 : a) velocity profile for glass

b) Lorentzian fit of the intensity of a sticked bead on the glass surface. (arbitrary unit for *I(z)*)

The velocity profile corresponding to a Poiseuille flow is fitted with a parabola. The slip length is then inferred from the position of the zero of this curve compared to the actual position of the wall.
The slip length for glass (wetting case) is found equal to 0±100nm, while, for OTS functionalized silicon substrates, one gets (non-wetting case) 200±300nm.

DISCUSSION AND CONCLUSIONS

The experimental method we present here allows us to measure velocity profiles in thin microchannels, with a few percent precision on the velocity, ±50nm-accuracy on the determination of the wall position, with respect to the fluid, and ±30nm accuracy for the position of the fluid layer where the measurement is performed. These characteristics allow to determine, with unprecedented accuracy (±100nm), slip lengths for water flows over glass ; this represents a substantial improvement (a factor of 6 or so) compared to previous work using a direct method (see Ref [1]). When applied to pyrex glass surfaces, one gets slip lengths equal to 0±100nm. For silicon surfaces, functionalized with octadecyltrichlorosilane, the accuracy is lower. One obtains 200±300nm for the slip length in this particular case.

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