Measurement of the slip length of water flow on graphite surface

Abdelhamid Maali, Touria Cohen-Bouhacina, Hamid Kellay

Measurement of the slip length of water flow on graphite surface

Abdelhamid Maali,[a] Touria Cohen-Bouhacina, and Hamid Kellay
Université Bordeaux1, Centre de physique Moléculaire Optique et Hertzienne, UMR 5798 du CNRS, 351 Cours de la Libération, 33405 Talence, France

(Received 26 October 2007; accepted 15 January 2008; published online 5 February 2008)

We present measurements of the hydrodynamic damping of an atomic force microscopy cantilever-tip immersed in water and approaching a mica surface or a graphite surface. Water completely wets the mica surface while it partially wets the graphite surface with a contact angle of 74°. The measurements show that the damping is higher on mica than on graphite giving a slip length of about 8 nm on this latter surface. © *2008 American Institute of Physics*.
[DOI: 10.1063/1.2840717]

The nonslip boundary condition at a solid interface is at the center of our understanding of fluid mechanics. The fluid velocity is assumed to be equal to the respective velocity of the surface. Recent experimental developments, allowing to manipulate and to control systems at micrometer and nanometre scales, have opened the way to severe tests of the nonslip boundary condition. Several experiments demonstrate an apparent slip of Newtonian liquids near solid surfaces.[1–11] The variety of methods used indicates that the observed slip is not an artifact of a single technique, but opens the debate to explain the wide range of the measured slip lengths. However, previous studies usually use surfaces that require special preparation and coating with hydrophobic molecules. Here, we study natural surfaces that do not require any preparation and are atomically flat which eliminates the contribution of the surface roughness to the liquid flow on the surface. Notice here that in contrast with experiments on coated surfaces that may be degraded during the measurements, especially in the surface force apparatus[2,3] and atomic force microscopy (AFM),[7–11] our surfaces are not altered since they are not coated. Furthermore, our experiments differ from previous AFM measurements[7–12] of the slip length which are carried out in the static mode, i.e., the monitored value is the deflection induced by the hydrodynamic force opposing the tip as it approaches the lower surface at high velocity. In such experiments, the distance between the surfaces is given by the imposed displacement plus the tip deflection due to the viscous hydrodynamic force. In our experiments, we vibrate the tip at very low amplitude (less than 1 nm) and we measure the amplitude and the phase as the tip approaches the surface at very low velocity giving the dissipation coefficient with high accuracy. The average hydrodynamic force is zero, in our case, and the distance between the tip and the surface is given directly by the imposed displacement. Our results show that the hydrodynamic force opposing the motion of the tip is lower for the graphite surface than for the mica surface indicating slip of water on the graphite surface with a slip length of 8 nm.

The boundary conditions combined with the Navier-Stokes equation give the Reynolds force acting on the cantilever tip as the tip approaches the surface,[13]

$$F = \frac{6\pi\eta R^2}{D}\frac{dD}{dt}f^*(D) = -\gamma_H\frac{dD}{dt}, \tag{1}$$

$$f^* = \frac{1}{4}\left\{1 + \frac{6D}{4b}\left[\left(1+\frac{D}{4b}\right)\ln\left(1+\frac{4b}{D}\right) - 1\right]\right\}, \tag{2}$$

where R is the tip radius, D is the gap between the tip and the surface, and γ_H is the hydrodynamic damping coefficient.

The above formula is valid for tip-surface distances D smaller than R. The function $f(D)$ characterizes the deviation from the nonslip boundary condition and b is the liquid slip length on the surface.

γ_H is the hydrodynamic damping. When the cantilever is immersed in a liquid, the total damping of the cantilever driven acoustically at the resonance frequency is given by the following expression:[14]

$$\frac{\gamma_{\text{tot}}}{\gamma_0} = -\frac{A_0}{A}\sin(\varphi) \times\left(\frac{Q_0}{\sqrt{1+Q_0^2}+2\frac{A_0}{A}\cos(\varphi)+\frac{A_0^2}{A^2\sqrt{1+Q_0^2}}}\right),$$

$$\gamma_{\text{tot}} = \gamma_0 + \gamma_H, \tag{3}$$

where A is the amplitude at a given distance between the tip and the surface, A_0 is the amplitude of the oscillation far away from the interaction region, φ is the phase, Q_0 is the quality factor, and γ_0 is the bulk viscous damping.

Let us emphasize that for very high quality factors ($Q_0 \to \infty$), we recover the usual expression for the damping coefficient: $(\gamma_{\text{tot}}/\gamma_0) = -(A_0/A)\sin(\varphi)$.

To measure the hydrodynamic damping close to the surface, we have used a commercial silicon cantilever having a large tip radius of 600 nm and having a spring constant $k_l = 0.7$ N/m (Team Nanotec GmbH Germany). The resonance frequency of this cantilever immersed in water is 20.2 kHz, the quality factor Q is 3.6 and the bulk viscous damping $\gamma_0 = (k_l/Q_0\omega_0) = 1.5\times10^{-6}$ N m^{-1} s. The cantilever is vibrated acoustically in water using our home made system[15] at amplitudes ranging from 2 to 8 Å. The experiments were performed using a commercial AFM (Nano-Scope III-extended Multimode, Veeco Instruments). The vibration amplitude and phase are measured using a lock-in amplifier (Stanford RS830) and the output data are stored

[a]Author to whom correspondence should be addressed. Tel.: 0 33 5 40 00 83 65. FAX: 0 33 5 40 00 69 70. Electronic mail: a.maali@cpmoh.u-bordeaux1.fr.

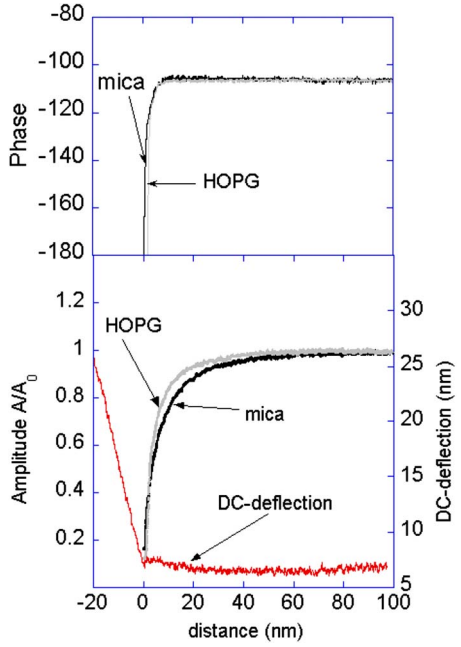

FIG. 1. (Color online) The measured phase (a) and amplitude (b) of the cantilever tip as it approaches the surface. The continuous line at the bottom represents the dc-deflection signal that allows us to get the contact position with a resolution of 1 nm.

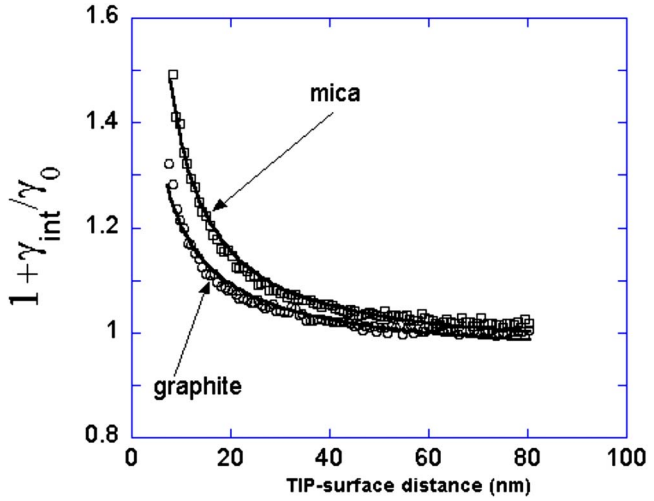

FIG. 2. (Color online) The damping coefficient extracted from the amplitude data. The solid lines are fits to the data using the expression given in the text.

with a digital oscilloscope TDS 3032 (10000 points/channel memory). The data are obtained by varying the tip-sample separation and recording the vibration amplitude and phase of the cantilever. In each cycle, the tip is approached at a velocity of 50 nm/s until the amplitude drops to zero (touching the surface) and then the tip is retracted at the same velocity. In our experiment, the thermal drift was about 0.3 Å/s.

Figure 1 shows the measured amplitude and phase as well as the deflection of the cantilever-tip approaching graphite and mica surfaces in water. The hydrodynamic damping reduces the vibration amplitude as the tip moves toward the surface. Note, however, that this reduction is more pronounced for mica than for graphite indicating a smaller hydrodynamic damping coefficient for this latter surface.

Using Eq. (3), we convert amplitude and phase data to get the damping coefficient versus the tip surface separation.

Figure 2 presents the damping coefficient extracted from the amplitude and phase data. We clearly see that the damping on the mica surface is higher than on the graphite surface. The data at very small distances ($D<5$ nm) are not shown since the simple harmonic oscillator model describing the cantilever vibration [Eq. (3) does not consider higher harmonics] breaks down due to the high values of the damping coefficient. The data corresponding to water flow on mica are fit using the Reynolds equation with the nonslip boundary condition which is valid for hydrophilic surfaces as shown recently with a high accuracy.[2,12] From the fit, we get the coefficient $6\pi\eta R^2/\gamma_0=4.1$ which is close the calculated value 3.8 taking the radius given by the manufacturer. We have then used this value to fit the damping on the graphite surface but allowing the liquid to slip by multiplying the Reynolds formula by the correction slip function[13] $f^*=1/4([1+(6D/4b)][[1+(D/4b)]\ln[1+(4b/D)]-1])$. The result gives a slip length $b=8\pm2$ nm. The measured slip length on the graphite surface is in agreement with the moderate value of the slip length of water flow on partially wetting surfaces obtained by molecular dynamics simulations.[16]

To conclude, we have presented measurements of the hydrodynamic damping of an atomic force microscope tip vibrating in water close to a solid surface. We have investigated two surfaces; one which is completely wet by water (mica) and a second surface which is partially wet by water (graphite). The measurements show that the damping is higher on mica than on graphite. By fitting our damping data we have extracted a slip length of 8 nm for water flowing on graphite while on mica, the slip length turns out to be too small to be measured (less than 2 nm).

Helpful discussions with J.-P. Aimé and E. Charlaix are acknowledged.

[1] E. Lauga, M. P. Brenner, and H. A. Stone, *Handbook of Experimental Fluid Dynamics* (Springer, New-York, 2005).
[2] C. Cottin-Bizonne, B. Cross, A. Steinberger, and E. Charlaix, Phys. Rev. Lett. **94**, 056102 (2005).
[3] Y. Zhu and S. Granick, Phys. Rev. Lett. **88**, 106102 (2002).
[4] T. Schmatko, H. Hervet, and L. Leger, Phys. Rev. Lett. **94**, 244501 (2005).
[5] L. Joly, C. Ybert, and L. Bocquet, Phys. Rev. Lett. **96**, 046101 (2006).
[6] P. Joseph and P. Tabeling, Phys. Rev. E **71**, 035303R (2005).
[7] E. Bonacoccurso, H.-J. Butt, and V. S. J. Carig, Phys. Rev. Lett. **90**, 144501 (2003).
[8] E. Bonaccurso, M. Kappl, and H.-J. Butt, Phys. Rev. Lett. **88**, 076103 (2002).
[9] J. W. G. Tyrell and P. Attard, Phys. Rev. Lett. **87**, 176104 (2001).
[10] V. S. J. Craig, C. Neto, and D. R. M. Williams, Phys. Rev. Lett. **87**, 054504 (2001).
[11] C. Neto, D. R. Evans, E. Bonaccurso, H.-J. Butt, and V. S. J. Carig, Rep. Prog. Phys. **68**, 2859 (2005).
[12] C. D. F. Honig and W. A. Ducker, Phys. Rev. Lett. **98**, 028305 (2007).
[13] O. I. Vinogradova, Langmuir **11**, 2213 (1995).
[14] C. Jai, T. Cohen-Bouhacina, and A. Maali, Appl. Phys. Lett. **90**, 113512 (2007).
[15] A. Maali, C. Hurth, T. Cohen-Bouhacina, G. Couturier, and J.-P. Aimé, Appl. Phys. Lett. **88**, 163504 (2006).
[16] J.-L. Barrat and L. Bocquet, Phys. Rev. Lett. **82**, 4671 (1999).