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Viscous interaction between surfaces: Studies by means of a capacitor ultradynamometer

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Abstract

A new electromechanical instrument for the investigation of interaction of surfaces enabling high resolution simultaneous displacement and force measurement with an electrical capacitor as a sensor is used to study viscous resistance of thin interlayers of liquid medium (10^{-1} M aqueous NaCl) between molten glass spheres.

The last decade was marked by a significant progress in studies of interaction between solid surfaces, mainly due to the new surface force apparatus based on measuring of distance between mica sheet samples by multiple beam interferometry [1,2]. Alternative approaches were also proposed, particularly the one with the use of piezoelectric sensor [3] . It has been reported earlier [4] about the development of a new experimental method of surface force investigation, based on an electrical capacitor as a high resolution sensor [5] . In the new instrument which is described below the sensor (capacitor) being separated from the samples is situated outside the measuring cell; this leads to significant simplification of the measurements and gives the freedom of choice of samples for investigation, of conditions and experimental regimes as well as of scopes of application. This work presents the results of investigation of hydrodynamic effects arising on the approach and on the removal of molten silica glass spheres in electrolyte solution, in the conditions under witch static interaction of surfaces is negligible.

The instrument is shown schematically in fig.I. One of the samples 2 is positioned with the help of micro drive unit 4 with respect to the other one I, which is installed at the bicantilever spring 3 (spring stiffness $k = IO^2$ N/m). Magnetoelectrical system (6,7) enables to apply external force to sample I [6] . For the regime of the variation of this loading force in time at a given speed α the equation of ballance of the forces is given by

$$\alpha\cdot\Delta t - k\cdot\Delta z + f = 0 \qquad (I)$$

where f is the force of interaction of the samples. The displacement Δz of sample I is measured using electrical capacitor 5, the plates of which (one of the plates constitutes part of the spring 3 construction) are separated by air gap. Electrical signals taken from the capacitor and the magnetoelectrical system pass through the electronic unit and finally come to the recorder producing force of interaction of samples, f, against the displacement, Δz, plots. Calibration was done in the ordinary way using microscope, weights and quartz filament (deformation of all parts of the device other then dynamometric spring are included in the calibration though contribute less than I%).

Effective mass of the spring carrying sample I was in the range of several fractions of gram. The instrument is protected from the convective motion of air in the room by a box and is installed on a suspended vibration protecting ground possessing typical mechanical frequencies of the order of I Hz. Measurements were done under usual laboratory conditions at room temperature (20 ± 2°C), displacement and force amplitudes of the residual noise were within 0,5 nm and $5\mathrm{xIO}^{-8}$ N, accordingly.

Spherical glass samples about 7 mm in diameter were molted at the ends of silica glass tubes immediately before installation in the instrument. The whole preparation of the experiment from melting of the sample to the beginning of the measurements occupied several minutes.

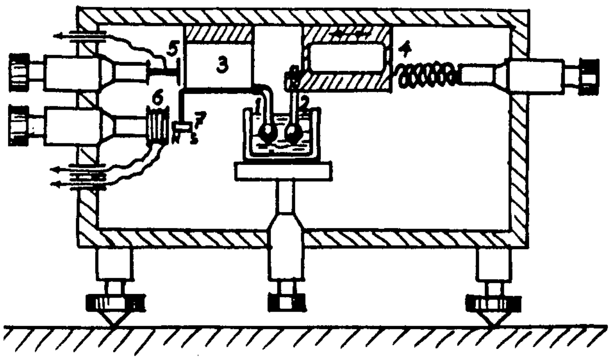

Fig.I. Ultradynamometer (schematically)
I,2 - the samples
3 - dynamometer (bicantilever) spring
4 - micropositioning unit
5 - capacitor (sensor)
6,7 - magnetoelectrical (loading) system

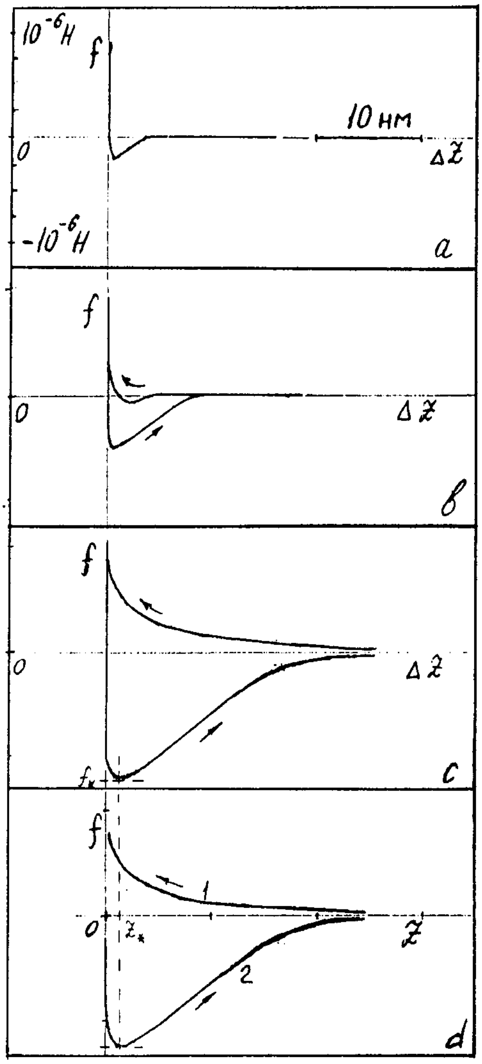

Fig.2.
Force of interaction f vs displacement Δz plots for glass spheres ($R=3{,}5\cdot IO^{-3}$ m) in 0,I M aqueous NaCl obtained during approach and separation at different loading rates: $\alpha = \mp\, 2{,}5\cdot IO^{-8}$ (a), $\mp 2{,}5\cdot IO^{-7}$ (b) and $\mp\, 2{,}5\cdot IO^{-6}$ N/sec (c); fig 2,d - theoretical force f vs distance z plots, for $\alpha = \mp\, 2{,}5\cdot IO^{-6}$ N/s, $\eta = IO^{-3}$ Pa·s. The scale is the same for all the curves and is indicated in fig.2a.

Test measurements in air reveal strong forces of adhesion typical for molecularly smooth surfaces of molten glass [7] ; in the measurements in bidistilled water exponentially decaying with the distance electrical double layer repulsion (according to the DLVO) is seen, in full agreement with the reported data for the glass [8] and quartz [9] . The addition of electrolyte (IO^{-I}M NaCL) removes the repulsion and enables immediate observation of hydrodynamic (viscous) forces, which are significant at sufficiently high external force loading speeds.

The results of measurements in salt solution are shown in fig.2 (a,b,c). Experimental curves are usually reproducible to within the limits determined by the noise. At low loading speeds (quasistatic regime) small attraction ($f < 0$) is observed at distances of the order of a few nm (fig.2,a) indicative of weak molecular forces. The curves for approach ($\mathcal{L} < 0$) and separation ($\mathcal{L} > 0$) virtually coincide. At high loading speeds $\mathcal{L}$ (fig. 2,c) viscous resistance results in a force, directed against the direction of movement of the sample ($f > 0$ on approach, $f < 0$ on separation). On approach the force increasses monotonously (under given loading regime $\mathcal{L} = \text{const} < 0$), on separation ($\mathcal{L} = \text{const} > 0$) the curve possesses a minimum (viscous "adhesion"); the depth of the minimum at sufficiently high $\mathcal{L}$ exceeds by many times the depth of the minimum observed under quasistatic conditions. Viscous force on separation of the surfaces is independent on the pre-history, i.e. on the magnitude and duration of action of the preliminary pressing force.

The force of interaction between two spherical (geometrical) surfaces having radius R, resulting from the viscous resistance of an interlayer having thickness z of continuous uniform medium having viscosity η is given by a know [IO,II] limiting ($z \ll R$) expression

$$f = -\frac{3}{2}\cdot\pi\cdot\eta\cdot R^2\cdot\frac{I}{z}\cdot\frac{dz}{dt} \qquad (2)$$

Dynamic terms and electroviscous effects [II] are negligible under the experimental conditions. The speed $v = dz/dt$ according to the equation (I) of movement can be expressed as

$$v = \frac{\mathcal{L}}{k\cdot(I - \frac{I}{k}\cdot\frac{df}{dz})} \qquad (3)$$

Substitution of (3) in the equation of hydrodynamic model results in

$$f(z) = -\frac{a\cdot\mathcal{L}}{z\cdot k\cdot(I - \frac{I}{k}\cdot\frac{df}{dz})} \qquad (4)$$

where $a = \frac{3}{2}\cdot\pi\cdot\eta\cdot R^2$. Particularly, when $df/dz = 0$ (which is true for "infinite" separation and that corresponding to the minimum arising in the surfaces separation regime) expressions (3) and (4) are reduced to $v_* = \mathcal{L}/k$ and

$$f_* \cdot z_* = -a \cdot \frac{\mathcal{L}}{k} \qquad (5)$$

accordingly.

Integration (numerical) of equation (4), for the spheres having $R = 3{,}5 \cdot 10^{-3}$ m approaching each other under constant loading rate $\mathcal{L} = -2{,}5 \cdot 10^{-6}$ N/s regime starting from sufficiently large distances for which f=0 (df/dz=0 and corresponding to the given value of $\mathcal{L}$ initial speed $v_* = \mathcal{L}/k = 25$ nm/s), gives curve 2 in fig.2,d. The result of integration of equation (4) with positive (separation) value $\mathcal{L} = +2{,}5 \cdot 10^{-6}$ N/s and with $f_* = -1{,}25 \cdot 10^{-6}$ N (experimental value for the minimum) is curve 2 in fig.2,d for which in accordance with (5) $z_* = 1{,}2$ nm.

It follows from the comparison of the data in figs. 2,c and 2,d that the experimental curves for both approach and separation of surfaces coincide (within the accuracy of the measurements) with the theoretical ones corresponding to continuous medium approximation and bulk viscosity of water. This gives a further support of the conclusions done earlier in [9,12] according to which water in interlayers as thin as a few nm retains its bulk value of viscosity. At lower thicknesses (a few molecular layers) continuous medium approximation is definitely unapplicable. For detailed analysis of the beheviour of such interlayers molecular structure of the medium as well as surface structure, elasticity of the samples and other factors shoud be taken into account. Additional experiments are necessary to be done at higher distance resolution (on reduction of the noise this is quiet possible with the use of the capacitor method). It should be noted, however, that at any displacement (Δz) resolution the question about the "absolute" distance (z) between solid surfaces is open to discussion.

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