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Measurement of two-dimensional viscoelasticity by EMS method

EMS 粘度測定システムによる 2 次元粘弾性計測

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1. Introduction

Recently developed disk-type electro-magnetically spinning (EMS) viscometer has been successfully employed also for measurements of mechanical properties of liquid surface, besides the bulk viscoity. For example, two-dimensional viscosity of the mono-molecular films adsorbed on the water surface was measured with the system. The forming process of the condensed layer of the protein molecules was also detected sensitively.

The physical origin of the viscosity is still an interesting theme of material science also in the three-dimensional world; one of the simplest phenomena is the increase in viscosity of colloidal systems with its concentration, however, the formulation of the viscosity in a dense region still remains unsolved, since the interaction and the transposition of the colloidal particles in the three-dimension are quite complex.

In the two-dimensional system, the hard circles freely floating in the media are considered to show contribution to the change in the viscoelastic properties, in which the modeling of the transposition of particles is much easier. The surface viscosity due to the particles dispersing on the liquid surface would be an ideal system for the experimental investigation. In this paper, we report the measurement of the surface viscosity of the liquid surface containing two-dimensional colloidal particles, which float on the surface. The disk-type EMS system could detect the distribution of the surface flow due to the rotation of the probe disk. It can also obtain the excess viscous torque, which is converted to the surface viscosity as a function of the surface concentration of colloidal particles.

2. Measurement of surface viscosity with Disk-type EMS

Figure 1 shows a schematic view of the experimental setup. A couple of magnets set below the sample cell generates the horizontal magnetic field and its rotation induces the eddy current in the probe disk. The disk is made of aluminum, whose

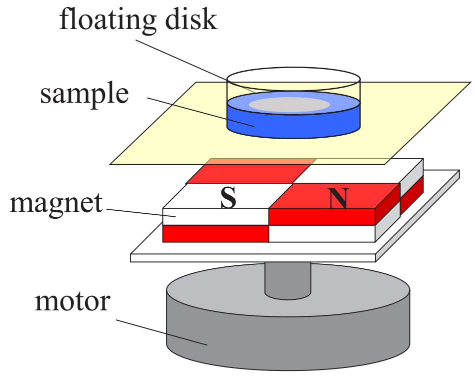

Fig.1. Schematic view of floating disk type electro-magnetically spinning viscometer.

diameter is 20 mm and the thickness is 0.3 mm. The disk floats on the sample surface by the surface tension and the buoyancy. The Lorentz interaction between the temporally modulated magnetic field and the induced current applies a torque to the disk to rotate on the sample surface following the motion of the magnetic field. The driving torque is proportional to the difference in the rotational velocities of the magnetic field Ω_M and that of the disk Ω_D, and the typical shear deformation rate is given by $\gamma=R_0\Omega_D/d$, R_0 and d being the radius of the probe disk and the depth of the sample, therefore, the viscosity is proportional to $(\Omega_M - \Omega_D)/\Omega_D$.

Here, we consider the contribution of the surface viscosity to the apparent increase in the resistant torque applied to the prove disk of EMS. A disk with diameter R_0 is floating on the center of the circular liquid surface with diameter R_1. The shear deformation rate of the liquid beneath the disk is given by, $\gamma(r) = r\Omega_D/d$, where r is the distance from the rotational axis. On the other hand, the surface around the disk flows as indicated later, and the rotational velocity of the surface is determined by the Navier-Stokes equation of $\Delta_S v_\theta=0$, where the suffix shows the operation in the surface. With the boundary conditions that $v_\theta=\omega R_0$ at $r=R_0$ and $v_\theta=0$ at R_1, the torque due to the surface viscosity η_S is given by,

$$v_\theta = \frac{R_0^{\,2}}{R_1^{\,2}-R_0^{\,2}}\Omega_D\{-r+\frac{R_1^{\,2}}{r}\}. \qquad (1)$$

The shear deformation rate under the surface flow is then given by $\gamma(r) = v_\theta/d$. The probe would feel the additional torque due to the surface viscosity which is obtained by substituting the contribution of the above bulk viscosity from the experimentally determined resistant torque.

3. Observation of rotational flow of colloidal surface

The sample is prepared as follows; a pure water is poured into a petri-dish and the depth is 5 mm. A disk plate made of aluminum is set just at the center of the water surface and then the two-dimensional colloid is fabricated by scattering a hydrophobic black micro particles on pure water surface. It is difficult to accurately measure the quantity of the colloidal particles spread on the water surface, therefore, we took photographs of the surface and estimate the surface concentration of the micro particles by measuring the depth of the black color of the image of the surfaces.

With these samples, we carried out the measurement of the distribution of the surface flow by observing the motion of the particles. The motion was taken as movies, through which the tangential speed of the particle is obtained. Figure 2 shows the result, in which we can see the rotational speed of the particle decreases with the reduced distance from the edge of the rotating circular disk. It shows that the free surface around the probe is suffered from the steady shear distortion, which dissipate the energy and works as the shear viscosity. The solid line shows the theoretical prediction derived from eq.(1).

The observed data dose not completely agree with the theoretical prediction, which might

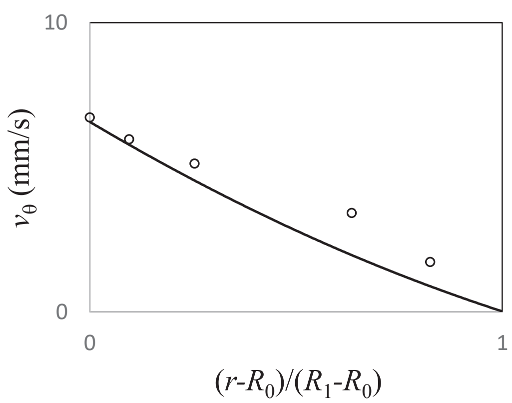

Fig.2. Distribution of the tangential velocity of the surface flow driven by the circular plate rotor. The solid line shows the theoretical prediction derived from eq.(1).

suggests that the present colloidal system would not be an ideal two-dimensional Newtonian fluid. More detailed experiments and analysis would be required for the examination of the two dimensional non-Newtonian fluids.

4. Measurement of surface viscosity of colloidal surface

Next, we measured the relation between the torque applied to the probe rotor and its rotational speed, and determined the surface viscosity as a function of the density of the surface colloidal system. Figure 3 shows the relation between the surface density of the colloidal particles and the torque additionally required for the rotation from that for the bare water surface. The vertical axis thus shows the quantity proportional to the magnitude of the surface viscosity. We can clearly see that the surface viscosity increases with the colloid density and the relation is almost proportional in the observed region.

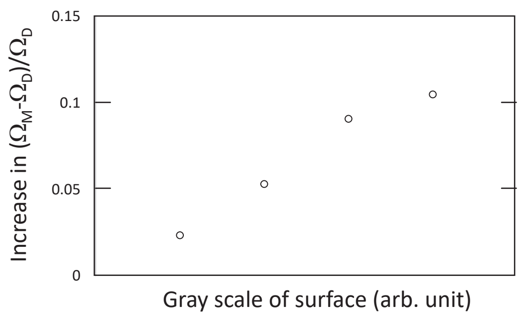

Fig.3. Colloid density dependence of the surface viscosity. The abscissa shows the deference in the darkness of the surface from a bare water surface. The vertical axis shows the excess viscosity applied to the probe.

In conclusion, we fabricate the surface colloidal system of the hydrophobic micro particles on pure water surface and successfully observed the surface viscosity by our disk-type EMS method. These macroscopic model of colloidal systems would be helpful for the understanding the rheological properties of the actual 3D colloidal systems.

References

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