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Measurement of ultra-low viscosity under steady shear flow by suspended EMS system

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1. Introduction

The role of fluids as materials for micro-functional soft devices are increasing recently. They are fabricated through new fluid processes including micro-fluidics and inkjet technologies, where fundamental physical properties such as viscosity and surface tension are quite important knowledge to design the micro fluid devices. Generally, in the above technologies, fluid with viscosity lower than 100 mPa･s are often employed, since the process time depends on the viscosity and surface tension as well as its spatial scale; The process time of the fluid deceases with decreasing viscosity. On the other hand from the viewpoint of the rheology measurement, it is quite difficult to measure the low viscosity even with a high-end model of the rheometer. It cannot measure the water viscosity of 1 mPa･s in the shear rate region lower than 100 s^{-1}. The performance of the viscosity measurement directly depends on the sensitivity and accuracy in determining the applied torque to the probe rotor of the rotational type viscometer. In the high-end model, the reduction of the harmful frictional torque is realized by employing the air-supported bearing, however, it is not free from the gas viscosity, which support the levitation of the rotor.

The point is how to keep the position and the posture of the rotor and how not to apply harmful torque other than that of the viscous resistance. A possible solution is the electro-magnetically spinning (EMS) system, which remotely drives the viscosity rotor; electro-magnetic interaction between the conductive rotor and the temporally modulation magnetic field gives the remote torque to the rotor.

In our previous paper, we introduced a suspended type EMS viscosity measurement system, in which the perpendicular rotational axis and the vertical position of the disk rotor is controlled by suspending the rotor by a thin metal wire. The angle of torsion of the wire is limited so that the restoring torque T_R does not exceed the viscous torque T_η applied to the rotor. In the actual experiment, the rotation of the rotor is restricted in the range, where the $T_R < T_\eta/100$ holds. The motion of the rotor is reciprocating and the measurement is regarded as quasi-steady flow.

To match the conventional methodology of the rheology measurement in the steady shear flow, we improved the system.

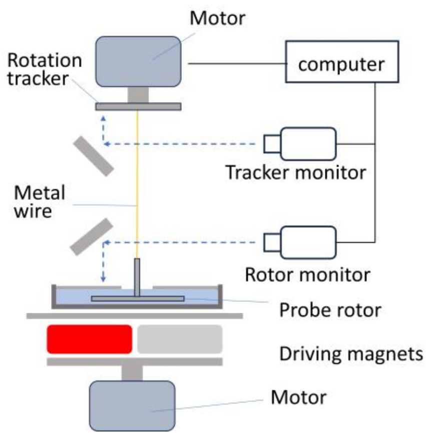

Fig.1 Schematic view of the suspended type EMS system improved for the measurement under steady shear flow.

2 Suspended EMS viscometer designed for steady shear flow measurement

Besides the reason described above, there are two major disadvantages in the quasi-steady measurement. One is the diffusion of the momentum in the gap between the moving rotor and the bottom of the sample container or the top cover. Here, the diffusion constant is the kinetic viscosity given by η/ρ, ρ being the density. To realize the homogeneous laminar flow, time of $\tau\sim\rho d^2/\eta$ is required for the momentum to diffuse the distance of the sample thickness h. In the present assumption, τ=1 s and we consider that the time of 10 s would be enough to realize the homogeneous laminar flow.

Another time constant is determined by the inertia and viscosity. After the constant torque is applied, the rotation approaches the steady state as ~exp(-t/τ) when the time constant is given by the ratio of the inertia moment and viscosity. We have to wait at least for this time constant, which is about 1 s in the usual experimental conditions.

Here, we estimate the resolution of the rotating angle of the rotation tracker. The viscous torque T_{vis} applied to the rotor of the parallel circular plate viscometer is given as,

$$T_{vis} = \pi\eta\omega {R_D}^4/2d$$

Here, R_D is the radius of the rotor, d the thickness of the sample, η the viscosity of the sample, ω the rotational speed of the rotor. When we expect the accuracy in determining the viscosity be α, the restoring torque due to the torsion of the supporting wire T_R should be less than αT_{vis}, which is described as,

$$T_R = \kappa\theta < \alpha T_{vis}, \quad (1)$$

Where $\kappa = (\pi G R_w{}^4/2L)$. Here, R_w and L are the radius and length of the supporting metal wire, G the sear modules of the material of the wire and θ is the angle of the torsion. Here, we consider the allowed angle of the twist, which is the difference in between the rotating angles of the rotor and the rotation tracker. Consider that the sample is pure water with viscosity of 1 mPa s and the shear rate of 1 s^{-1}, the allowed difference is calculated to be 0.13 rad for $\alpha=10^{-2}$. The developed angle tracker described below can safely keep the difference in the required range of the angle.

3 Experiment and results

Figure 1 shows the schematic view of the suspended EMS viscosity measurement system equipped with the automatic rotation tracker. The sample container is a petri dish with inner diameter of 90 mm. The probe rotor is composed of a circular plate made of acrylic resin, a supporting rod and a small aluminum plate, which detects the torque through the electro-magnetic interaction from the driving magnets set below the sample container. The radius of the probe rotor is 40 mm and the thickness is 1 mm. The upper end of the supporting rod is suspended by a gold wire with a diameter of 30 μm and length of 0.3 m. The length can be adjusted owning the required value of the restoring force against the torsion. The disk plate is immersed in the sample fluid and sandwiched by the bottom of the sample cell and the top plate. The upper and the lower gaps are set to be equal by adjusting the height of the supporting position by the metal wire. Here, the summation of the gaps is accurately determined by the bearing ball spacers, therefore, the slight change in the perpendicular position of the disk is compensated.

The upper end of the supporting wire is held by the automatic angle tracker. The rotational motions of the rotor and tracker are monitored by video cameras and the rotational speed of the tracker is controlled so the difference in between the two angles is kept in the condition described in Eq. (1).

The rotation of the angle tracker is driven by a DC servomotor purchased from Oriental Motor Co. Ltd., which is controlled following the image date of the by a computer.

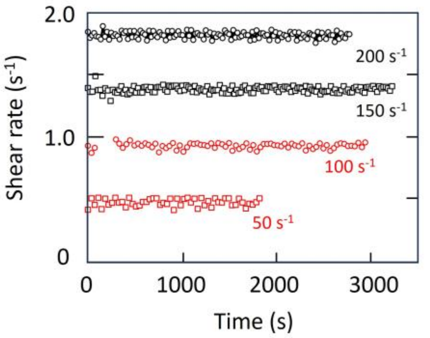

Fig.2 Stability of shear rate of suspended EMS equipped with angle tracker. The rotational speeds of driving magnets are 200, 250, 100 and 50 s^{-1} from the top to the bottom.

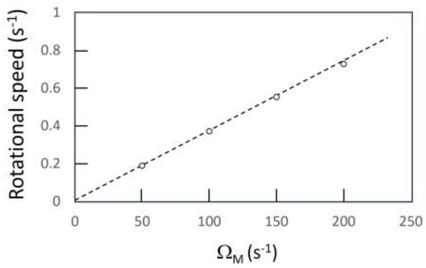

Fig.3 Relation between the rotational speeds of magnetic field and probe, which is proportional to the applied torque and shear rate respectively.

The sample is pure water. The torque is controlled so that the shear rates would be around 1 s^{-1}. Figure 2 shows the rotation of the probe rotor plotted against time. As shown, the angle linearly increases and the we confirm the steady flow is realized for a long measurement time.

The relation between the shear rate and applied torque is shown in Fig.3. Here, the quantity Ω_M-Ω_D is the difference between the angular velocities of the driving magnetic field and the probe rotor, which is proportional to the applied torque. As shown, the data is well plotted in the linear relation passing the origin.

In conclusion, we improve our suspended EMS system for the measurement viscosity in the steady flow for especially ultralow shear rate region. The results applied for various kinds of lowly viscous liquids would be shown in the conference presentation.

References

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