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EMS viscometer designed for measurement of low viscosity in low shear rate region

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1. Introduction

In the field of rheology, the dependence of the viscosity on the shear deformation rate gives dynamic information of the microscopic internal degrees of freedom, which couples to the flow of the fluids. The shear rate dependent viscosity is called flow curve, which is commonly discussed to investigate the molecular dynamics in complex fluids, such as polymer solutions, colloids, emulsions and so on. However, the lowest shear rate of the high-end model rheometer for lowly viscous fluids, such as pure water remains as low as 10^2 s^{-1}.

Recently, lowly viscous liquids having complex internal structure attracts great interest as new functional fluids. A typical example is human blood, whose viscosity is only several times larger than the pure water in the shear rate region above 500 s^{-1}, which corresponds to that in the capillary vessels, but shows shear thinning at even less than the shear rate of 10 s^{-1}. In this study, we propose a new application of the electro-magnetically spinning (EMS) viscosity measurement system to extend the measurement range to lower shear rate for lowly viscous samples.

Here, let us briefly introduce the principle of the EMS system. Probe rotors of the system is made of conductive materials and the rotating magnetic field is applied. Then the current is induced by the temporal modulation of the magnetic field and the Lorentz interaction between the induced current and the applied magnetic field generates the torque for rotor to rotate following the rotation of the magnetic field.

In this study, we propose a very simple but practical improvement of the EMS system to measure the low viscosity in a low shear rate region. The goal is set to detect water viscosity at shear rate below 1 s^{-1}, with the accuracy better than 10%.

2 Suspended EMS viscometer

Figure 1 shows the schematic view of the suspended EMS viscometer. The probe rotor to detect the sample viscosity is a parallel disk with a thin center rod, which is suspended by a thin metal wire at the top of the center rod. A part of the rotor is made of aluminum and driven remotely by rotating magnets set below the sample container. 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.

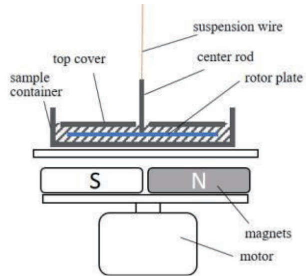

Fig.1 Schematic view of the suspended type EMS viscosity measurement system.

Along this schematic figure, we introduce the procedure of the viscosity measurement. The disk probe is supported by the metal wire, whose rotation is suffered from the restoring force against the distortion of the wire. The restoring torque is proportional to the rational angle θ as $T_G = \kappa\theta$, where the spring constant is given by $\kappa = (\pi G R_w{}^4 / 2L)\theta$, where R_w, L and G are the radius, length and Young's modulus of the wire with a circular cross section. The rotational motion of the suspended rotor is then given by, $I\ddot{\theta} = -\kappa\theta - \Gamma\dot{\theta}$, where I is the moment of inertia of the probe and the decay coefficient Γ due to the viscosity is given by $\Gamma = \pi\eta R_D{}^4/h$, with the sample viscosity η and the sample thickness h. By considering a parallel circular plate with radius R_D, thickness d and density ρ, the inertia moment is given as $I = \pi\rho R_D{}^4 d/2$. Two types of the viscosity measurement are possible using this probe.

(i) *Observation of free decay oscillation after initial distortion*

If we can give a stable initial state with a finite rotational angle and/or initial speed, the decay

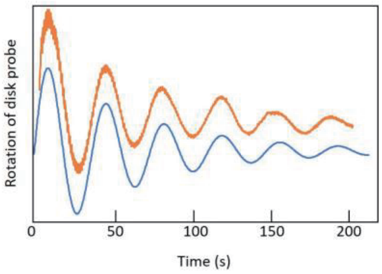

Fig.2 Decay oscillation of viscosity probe in air.

oscillation is expected. Generally, it is quite difficult to give s stable initial state from the pendulum type rotor, to give only the rotation without any translational motion, however, the electro-magnetic excitation is appropriate for the purpose.

Disadvantage of this method is that the motion is harmonic and the measurement is not necessarily carried out in the steady state, however, it is quite sensitive for the low viscosities. To determine the ability of the system, we carried out the measurement of the viscosity of the atmosphere, the mixed gas of nitrogen and oxygen. Figure 2 shows the decay oscillation of the rotor in the air at temperature of 25 ° C. Theoretical behavior is calculated using R_D=4x10^{-2} m, ρ=1000 kg/m^3, R_w=2.5x10^{-5} m, d=10^{-3} m, and air viscosity η_{air}=1.85x10^{-5} Pa s, and the decay oscillation is shown as a blue curve in Fig.2. As shown, the experimental result of the red line and the theoretical prediction agree well, showing that the measurement of gases is possible with a simple improvement of the conventional EMS method.

(ii) *Quasi-steady state measurement*

We can regard the motion of the rotor as steady state when the viscous torque satisfactorily exceeds the restoring torque of the distorted suspension wire, of which condition is expressed as $\Gamma\ d\theta/dt >> \kappa\theta$. This equation determines the range of the angler velocity $d\theta/dt$; we estimate the range of the angle here by assuming that the sample is pure water with viscosity of 1x10^{-3} Pa s, using the experimental configuration, $d\theta/dt$ is 2.5x10^{-2} rad/s. If we observe the viscosity in this region, we can determine the viscosity under the steady flow.

Here, we have to pay attention to two time constant to confirm the fluid system is steady. One is the homogeneity of the laminar flow in the gap between the moving rotor and the bottom of the sample container or the top cover. Naive-Stokes equation represents diffusion process of momentum, where the kinetic viscosity is the diffusion constant. To realize the homogeneous laminar flow, time of $\tau \sim \rho h^2/\eta$ is required for the momentum to diffuse the distance of the sample thickness h. In the presentt 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 $\tau = I/\Gamma$. We have to wait at least for this time constant, which is about 1 s in the present experimental conditions. Therefore, we applied the periodical square waveform of torque with a period of 20 s. Figure 3 shows the rotation of the rotor in pure water, in which the angle and the angular velocity are plotted. The applied torque is square and we can see that the rotational speed approaches constant within the time

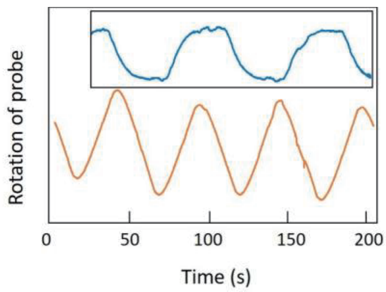

Fig.3 Quasi-steady measurement of water viscosity. The inset shows the rotational velocity.

of several seconds.

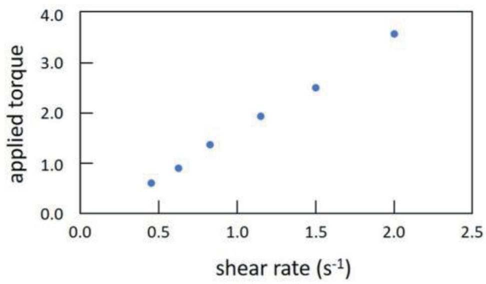

Fig.4 viscosity of water measured below shear rate region of 2 s^{-1}.

The rotational velocity at the steady state are measured changing the magnitude of the apllied torque; the rotational speed of the magnetic field is swept and the results are shown in Fig. 4. The horizontal and perpendicular axes corresponds to the shear deformation rate and the viscous torque, respectively, whose gradient gives the sample viscosity. As shown, the experimental data are fitted by a straight line crossing the origin, which shows that the low viscosity of 1 Pa·s can be detected in the shear rate region below 1 s^{-1}.

References

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