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Proceedings of Symposium on Ultrasonic Electronics, Vol. 32 (2011) pp. 183-184
8-10 November, 2011

Accurate viscosity evaluation of various liquids by EMS system
ＥＭＳシステムによる各種水溶液の高精度粘性測定

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1. Introduction

The methodology of the low viscosity measurement has been conventional and almost limited to the capillary method because of the difficulty in measuring small stress or torque applied to the moving devices. However, the recent progress in the micro-fluidics is remarkable, in which the viscous term plays very important role in determining the dynamic behavior of the micro fluid in the micro processes, such as the ink jet and the spin coating.

In this paper, we propose a very simple method of measuring low viscosity with high accuracy better than 1% in determining the viscosity of 1 mPa · s. Electro-magnetically spinning (EMS) viscometer is our recent innovation, which is featured by as a non-contact measurement of the viscosity.

The principle is the remote drive of the metal sphere rotor in the confined sample by means of the electro-magnetically application of the torque. The detail is described elsewhere and we introduce here a brief account. A metal sphere is set at the bottom of a concave sample cell, on which the magnetic field rotating is applied. The Lorentz force working to the current induced by the temporally modulated magnetic field drives the sphere so that it rotates following the magnetic field.

The viscous torque roughly equals to the friction at the angular frequency of Ω=10 s^{-1} for the viscosity of 1 mPa· s. The settlement to improve the accuracy can be found if we handle the harm of the friction.

In our new system, we employ a disk rotor instead of a sphere, which floats on the sample surface with the buoyancy and surface tension. The newly developed remote driving system of the rotor is different from the previous system and we first introduce the principle in the next section. We also demonstrate the measurement of the pure water viscosity with accuracy better than 1 % in the following description.

2. Principle of Viscosity Measurement

The principle of the non-contact induction of the torque to the rotor is similar with that of our previous EMS viscometer, in which the temporally modulated magnetic field generates the current in the electrically conductive rotor and the Lorentz interaction between the current and the magnetic field drives it to rotate following the motion of the magnetic field. The geometrical configuration is, however, modified to settle the problem of the conventional Zimm type and the recent EMS viscometers.

A schematic view of the newly developed viscometer is shown in Fig.1.A disk rotor is made of metal foil and has an edge wall to stably floats on the sample liquid surface with buoyancy. Here, we calculate the torque applied to the floating disk by the rotating magnetic field. We assume that the magnetic field directs along z-direction and the rotation can be represented by,

$$B_z = B(r)\exp\{i(\omega t - n\theta)\}, \quad (n = 1, 2, 3\cdots)$$

where $r = (x^2 + y^2)^{1/2}$. The conductive disk is satisfactorily thin and set in x-y plane. The electric field induced following the modulation of the magnetic field satisfies the equation of $\nabla \times \mathbf{E} = -\partial \mathbf{B} / \partial t$, and the current is given by $\mathbf{i} = \sigma \mathbf{E}$, σ being the conductivity. The Lorentz force is then given by $\mathbf{F} = \mathbf{i} \times \mathbf{B}$ and the torque is then calculated by, $\mathbf{T} = \int \mathbf{r} \times \mathbf{F} d\mathbf{s}$. For the simplicity, we show the result for the typical case that the magnetic field is expressed as the Bessel function and is written as

$$B(r) = B_0 J_n(kr). \qquad (1)$$

The total torque with respect to z-axis are then calculated to,

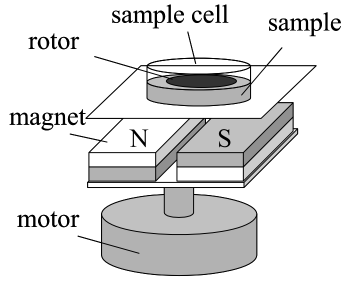

Fig.1 Schematic view of the experimental system.

$$T = \frac{\pi\sigma n\omega B_0^{\ 2}}{k^2}\int_0^R J_n(kr)^2\ dr\,,$$

with the radius of the disk R. It would be reasonable to assume the order of the wavenumber k to $k \approx 1/R$.

The result shows that a temporally constant torque is applied to the disk, which is proportional to the rotational speed and the square of the magnitude of the magnetic field. Here, the angular frequency in the above equation should be replaced the difference between the frequencies of the magnetic field and the disk, $\Omega_M = \Omega_D$.

3. Experiment

The disk rotor is 30 mm in diameter and is made of thin aluminum foil with thickness of 0.1 mm, which has an edge to float on the sample liquid surface by the buoyancy. The sample cell is 44 mm in inner diameter and 15 mm in depth. The typical volume of the sample required is 3 mL, and the thickness is about 0.5 mm.

A pair of magnets are set just below the sample cell through the top cover facing upward and this configuration corresponds to n=1 in eq.(1). The magnitude of the magnetic field is about 50 mT at the plane including the disk.

The torque applied to the rotor can be calculated with the above formula, however, it is more practical to obtain the relation between the sample viscosities and the flow curves representing the disk rotation dependent on the rotational speed of the magnetic field. Figure 2 shows the relation between the rotational speed of the disk Ω_D and the difference of the rotations of the magnetic field and the disk, Ω_M-Ω_D, which are proportional to the shear deformation rate and the torque applied to the disk, respectively. Samples used are the standard liquids for the viscosity purchased from Shin-Etsu Silicone Co. Ltd. and the viscosities are 1.0, 2.0 5.0 and 10.0, respectively. The gradient of the curve roughly gives a measure of the viscosity for the Newtonian liquids

The rotation of the magnetic field is controlled by a speed controllable motor and the motion of the disk is recorded by a video camera and the movies are analyzed to determine the rotational speed of the disk. The rotation of the magnetic field is swept in the range of 1 s^{-1}<Ω_M<10 s^{-1}. Temperate was controlled to 25+0.1 C by a thermostatic bath throughout the experiments. We can see that the curves in Fig.2 are smooth and are clearly distinguishable to each other. Roughly from the scatter of the data, we conclude that the resolution of the viscosity measurement is better than 5%.

Figure 3 shows the result of the viscosity

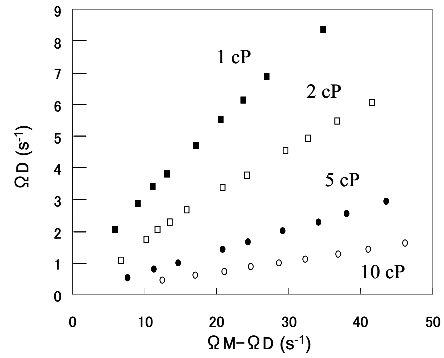

Fig.2 Relation between the relative rotational speed of the magnetic field and disk rotor.

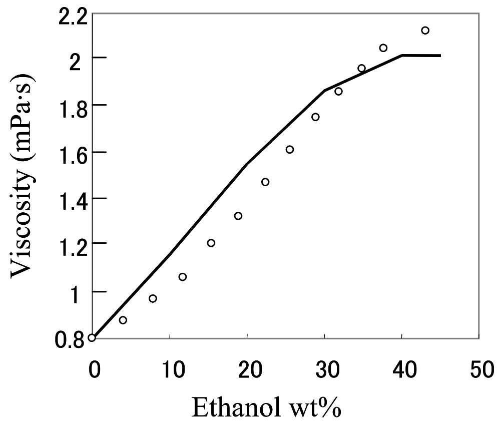

Fig.3 Viscosity of aqueous solution of ethanol measured by disk-type EMS method. The solid line shows the literature value determined by Bingham, et.al.

measurement of the aqueous solution of ethanol. The solid line shows the literature value obtained by the capillary method. The result shows very good accuracy and reproducibility in determining low viscosity. The actual measurement apparatus would appear at the presentation.

References

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