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Measurement of viscosity of liquid in micro-crevice

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ABSTRACT

A measurement of viscosity and rheology of a liquid confined within tight space with scientific accuracy typically has been a challenge. In order to measure viscosity of the liquid in micro-crevice at low shear rate a micro-crevice viscometer (MCV) is developed by modifying an interfacial-viscometer. The viscosity of water and hydrocarbons (C_{10}, C_{12}, C_{14} and C_{16}) was measured with the viscometer in this study. The results show that the viscosity measured at low shear rate by the micro-crevice viscometer and calculated with conventional methods has fine accuracy and repeatability when micro-crevice thickness is big and fixed. The liquid in small micro-crevice or confined within small space exhibit higher viscosity than bulk value and the viscosity should increase as the micro-crevice thickness decreases. Due to over-effect of *h* on viscosity calculation leads to water and hydrocarbons viscosity decrease as *h* decreases which do not indict the nature of the liquids in micro-crevice or confined within small space, a new calculating method based on influence of solid surface on liquid should be developed.

1. Introduction

The properties of liquids confined within very small spaces, such as narrow pores or thin films, are generally quite different from their bulk properties whenever the pore dimensions or film thickness falls below a few molecular dimensions. Gee et al. [1] measured the shear forces between two molecularly smooth solid surfaces separated by thin films of various organic liquids. They found that for films less than ten molecular diameters they exhibit more solid-like behavior. All solid-like films exhibit a yield point or critical shear stress, beyond which they behave like liquid crystals or ductile solids undergoing plastic deformation. The "effective" viscosity in molecularly thin films can be 10^5 times the bulk value, and molecular relaxation times can be 10^{10} times slower. These properties depend not only on the nature of the liquid, but also on the atomic structure of the surfaces of solid where the liquid is confined, the normal pressure, and the sliding direction and its velocity.

Noirez and Baroni [2] study is focused on the low-frequency response (10^{-1}–10^2 rad s^{-1}), low shear strain stresses (0.1–2%) when water is confined in 0.125 mm gap thickness at room temperature. Their result indicates that when water is firmly anchored on the surfaces, its response to a weak mechanical solicitation is solid-like. They also found that a range of water thicknesses from 0.055 mm to 0.500 mm that indicates similar elastic response, with a trend of decreasing elasticity with increasing gap and no longer measurable at larger thicknesses. The water elasticity is in agreement with shear moduli measured with this method on other liquids (heptadecane, glycerol, o-terphenyl, polymer melts) [3–7].

These studies indicate that when liquid is confined within small gap thickness less than 0.500 mm they exhibit higher viscosity and elasticity than in a bulk phase. The viscosity and elasticity of liquids decreases from solid surface to bulk continuously. In other words, liquid exhibits long-range solid-like correlations at a macroscopic scale away from any phase transition. It is obvious that these results provide new fundamental insights into the state of thin liquid films, and have a bearing on understanding of boundary friction, thin-film lubrication, stress–strain properties of solids and the liquid flow or migration at the molecular level and micro-crevice of millimeters. However, the measurement of viscosity and rheology of liquid confined within very small space between solid surfaces at low shear rate is still a challenge both scientifically and technically.

In order to measure viscosity of liquid confined in micro-crevice of millimeters at low shear rate we developed a micro-crevice viscometer (MCV). In this paper, we studied two measure methods with the viscometer and three conventional calculation methods for measuring viscosity of liquid confined in micro-crevice of millimeters at low shear rate. The results of the study show that viscosity of liquid in micro-crevice measured at low shear rate and calculated by these methods has fine accuracy and repeatability when micro-crevice thickness is big and fixed. However, when

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Nomenclature and symbols

C_{10} decane
C_{12} dodecane
C_{14} tetradecane
C_{16} hexadecane
Damped oscillation method liquid viscosity measured as low-plate is stationary while up-plate oscillates driven by torque of steel wire
Shear method (measurement) liquid viscosity measured with low-plate rotates at Ω steadily driven by a motor
Shear method (calculation) liquid viscosity is calculated with Eq. (16)
Oscillation moment balance method liquid viscosity is calculated with Eq. (28)
Oscillation energy balance method liquid viscosity is calculated with Eq. (48)
A oscillation amplitude of up-plate
A_0 oscillation amplitude of up-plate at initial time
B integral coefficient of area, m^3
c damping coefficient of liquid act on up-plate, s^{-1}
C integral coefficient of time, t^2
d diameter of plate, m
d_p particle diameter, m
$E_{el,\,0}$ initial elastic potential energy of steel wire, J
$E_{el,t}$ elastic potential energy of steel wire at time t, J
$E_{r,\,0}$ initial rotational kinetic energy of up-plate and fixing system, J
$E_{r,\,t}$ rotational kinetic energy of up-plate and fixing system at time t, J
E_{dis} energy dissipation induced by resistance of liquid, J
F force of liquid act on up-plate, N
h micro-crevice thickness between plates, m
I rotational inertia of up-plate and fixing system, N m s^{-2}
K torque coefficient of steel wire, N m
M torque of liquid act on up-plate, N m
M_r torque of liquid act on up-plat at r from the center of plate, N m
n power-law index
r radius from center of plate, m
R plate radius, m
s oscillation arc length, m
t time, s
V velocity of liquid in micro-crevice, m/s
z vertical distance from low-plate surface, m
α angular acceleration, rad s^{-2}
α_t angular acceleration of up-plate at t, rad s^{-2}
β resistance coefficient, N m s^{-1}
γ_r shear rate at r from the center of plate, s^{-1}
γ_R shear rate at R from the center of plate, s^{-1}
η viscosity of liquid, Pa s
η_{app} apparent viscosity of liquid, Pa s
θ rotation angle of up-plate, rad
θ_0 initial rotation angle of up-plate, rad
θ_t rotation angle of up-plate at time trad
τ_r shear stress act on up-plate at r from the center of plate, N
Ω rotation angular velocity of low-plate with shear method or of up-plate with damped oscillation method, rad s^{-1}
Ω_0 initial rotation angular velocity of up-plate, rad s^{-1}
Ωt rotation angular velocity of up-plate at time t, rad s^{-1}
φ phase angle, rad
ω_0
ω angular frequency of up-plate and fixing system oscillates in the air, s^{-1}
angular frequency of up-plate and fixing system oscillates with contacting liquid in micro-crevice, s^{-1}

micro-crevice thickness is small the viscosity calculated with these methods has big difference. We also found that as micro-crevice thickness decreases viscosity is not expected increase, but decreased far less than bulk value. These phenomena imply that due to the effect of micro-crevice thickness the viscosity calculated with these conventional methods deduced from physics can't indicate the nature of liquid confined in small pace. Therefore, a new method based on colloid and surface science for calculating viscosity of liquid confined in micro-crevice need to be developed.

2. Material and methods

2.1. Measurement method

The micro-crevice viscometer (MCV) is developed by modifying an interfacial-viscometer based on measuring principle of parallel plate viscometer [8,9] and oscillation viscometer [10,11]. The water used in this study is double distilled water and the hydrocarbons (C_{10}, C_{12}, C_{14} and C_{16}, mass fraction purity $>0.99\%$) were supplied by Beijing Modern Oriental Fine Chemicals Co., LTD.

The measure part of the micro-crevice viscometer consists of two plates with the same diameter (d) as shown in Fig. 1. The smallest micro-crevice thickness between plates (h) can be adjusted in 10 μm. The ratio of plate radius (R) and the micro-crevice thickness meet the following relationship:

$$\frac{h}{R} \ll 1 \tag{1}$$

The ratio of particle (ions, molecule, molecular aggregation or solid particle, etc.) diameter (d_p) in liquid and micro-crevice thickness meet the following relationship:

$$\frac{d_p}{h} \ll 1 \tag{2}$$

Liquid is injected in micro-crevice between two plates. The resistance of the air on plates for viscosity measurement is ignored. The viscosity of liquid in micro-crevice can be measured with shear method or damped oscillation method. When viscosity is measured with shear method [8,9] low-plate is driven by a motor steadily. The schematic diagram of measure part with shear method is shown in Fig. 1.

When torque of steel wire is balanced by torque of liquid act on up-plate, the rotation angle of up-plate (θ) was measured. At steady state, the velocity profile of liquid in micro-crevice is shown in Fig. 2. Velocity of liquid in micro-crevice is calculated by Eq. (3):

$$V = \Omega R\left(1 - \frac{z}{h}\right) \tag{3}$$

where R is radius of plates, Ω is rotation angular velocity of low-plate, z is vertical distance from low-plate surface.

Shear rate (γ_r) and shear stress (τ_r) at r from the center of plate is as Eqs. (4) and (5), respectively. r is radius from center of plate, η