

Viscosity of water and hydrocarbon changes with micro-crevice thickness



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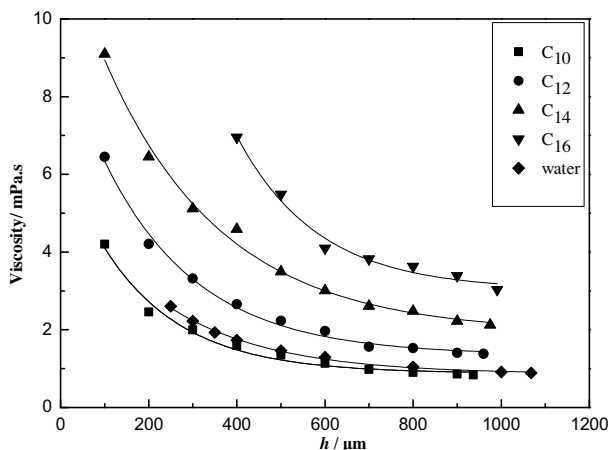
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HIGHLIGHTS

- Viscosity of fluid in micro-crevice increases as thickness of the micro-crevice decreases.
- Viscosity increasing of fluids in small micro-crevice is correlated to energy decay and energy dissipation rate of the measuring system.
- Viscosity of the fluid in small micro-crevice is affected by solid surface and fluid molecule structure.

GRAPHICAL ABSTRACT

Viscosity of water and hydrocarbons vs h at 25 °C. Due to effect of solid surface and fluid molecule structure the viscosity of fluid in micro-crevice increases as thickness of the micro-crevice decreases.



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ABSTRACT

Viscosity of C₁₀, C₁₂, C₁₄, C₁₆ and water in micro-crevice of 100–1500 μm was measured with a proprietary micro-crevice viscometer that was developed earlier in our laboratory. The viscosity was calculated based on a newly proposed model for fluid in the scale of micro-crevice stated above. The results of the study show that the viscosity of the fluids in small micro-crevice increases as the thickness of the micro-crevice decreases at low shear rate (1.34–9.07 s⁻¹). The viscosity of the fluids is correlated to energy decay and dissipation rate of measuring system. When $h < h_{dis}$, C₁₀, C₁₂, C₁₄, C₁₆ and water in small micro-crevice become dilatant fluid, therefore, η , E_{dec} , $E_{dis-rate}$ and τ of the fluids increase as h decreased. Due to h_{dis} of C₁₀, C₁₂, C₁₄ and C₁₆ is increased with increasing molecular mass, and h_{dis} of water which is a polar molecule is bigger than that of C₁₆ which is a non-polar molecule, the properties of fluid in small micro-crevice are not only affected by solid surface but also by fluid molecular structure.

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1. Introduction

Movement of water in porous rock, soil and other porous mediums [1] and migration of oil in reservoir [2] are characterized as fluid flows in small confined space and low shear rate. The flow

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Nomenclature

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
Oscillation moment balance method	Liquid viscosity is calculated with Eq. (4)
Oscillation energy balance method	Liquid viscosity is calculated with Eq. (5)
a	a coefficient
A	Oscillation amplitude of up-plate
A ₀	Oscillation amplitude of up-plate at initial time
b	a coefficient
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	a coefficient
D	a coefficient correlated to fluid viscosity, Pa s
E	Energy of the measuring system, J
E _{dec}	Energy decay that is defined as the elastic potential energy ratio of the steel wire of two neighbor periods
E _v	Energy dissipated by unit volume fluid, Jm ⁻³
E _{dis-rate} or dE _v /dt	Energy dissipation rate by unit volume fluid, Jm ⁻³ s ⁻¹
E _{el,t}	Elastic potential energy of steel wire at time t, J
E _{r,t}	Rotational kinetic energy of up-plate and fixing system at time t, J
F	Force of moving plate act on fluid in x dimension, N
f	a coefficient
h	Micro-crevice thickness between plates, m
h _{dis}	Micro-crevice thickness of the fluid become a dispersion, m
I	Rotational inertia of up-plate and fixing system, Nm s ⁻²
K	Torque coefficient of steel wire, Nm
k	Instrument factor, Pa s
n	Index
R	Plate radius, m
S	Shear area of fluid, m ²
t	Time, s
T	Oscillation period of the up-plate and fixing system, s
u	a coefficient
V	Volume of the fluid in micro-crevice, m ³
α	Angular acceleration, rad s ⁻²
α _t	Angular acceleration of up-plate at t, rad s ⁻²
η	Viscosity of fluid, Pa s
τ	Shear stress, Pa
γ or dv/dy	Shear rate, s ⁻¹
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 t, rad
Ω	Rotation angular velocity of up-plate with damped oscillation method, rad s ⁻¹
Ω ₀	Initial rotation angular velocity of up-plate, rad s ⁻¹
Ω _t	Rotation angular velocity of up-plate at time t, rad s ⁻¹

behavior of these fluids in their environment is interest by both scientists and engineers for a long period. However, the measure-

ment of viscosity and rheology of fluid confined within small space between solid surfaces at low shear rate is still a challenge both scientifically and technically.

Roger G. Horn and Jacob N. Israelachvili [3] and Gee ML et.al [4] measured the shear force between two molecularly smooth solid surfaces separated by thin film 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 ductile solids undergoing plastic deformation. The “effective” viscosity in molecularly thin films can be 10⁵ times the bulk value, and molecular relaxation times can be 10¹⁰ times slower. These properties depend not only on the nature of the liquid, but also on the atomic structure of solid surfaces where the fluid is confined, the normal pressure, and the sliding direction and its velocity.

Jacob Klein and Eugenia Kumacheva [5] also fund when octamethylcyclotetrasiloxane (OMCTS) was confined between two flat mica surfaces, the fluid is liquid-like as the distance between the mica surfaces is 6.2 nm, i.e. seven monolayers of OMCTS. The effective viscosity of the fluid is about 3 P (poise) at shear rate of 258 s⁻¹ and 23.5 °C. When the distance between the mica surfaces is 5.4 nm, i.e. six monolayers of OMCTS, the fluid is solid-like and effective creep viscosity of the fluid is larger than 6 × 10⁷ P at 23.5 °C. However, the viscosity of OMCTS in bulk phase is only 2.6 cP at 25 °C. They also measured cyclohexane and toluene the results are similar to that of OMCTS.

Recently Noirez and Baroni [6] found the low-frequency dynamic response of liquid water and it showed an elastic response at a sub-millimeter thickness between alumina substrate. This result is obtained by applying a weak mechanical stress efficiently transmitted to the fluid by improving the boundary conditions between fluid and the substrate. Their study is focused on the low-frequency response (10⁻¹–10² 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 at different water thicknesses the elastic response persists at least from 0.055 mm up to 0.500 mm, decreasing with increasing gap and no longer measurable at larger thicknesses. That observation is in agreement with shear moduli measured with the method on other liquids (heptadecane, glycerol, o-terphenyl, polymer melts) [7–11].

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 at low shear strain stresses. The viscosity and elasticity of liquids decrease 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.

In our previous study [12], to measure viscosity of liquid confined in micro-crevice of micrometers at low shear rate, we developed a micro-crevice viscometer (MCV) and the viscosity of water and hydrocarbons (C₁₀, C₁₂, C₁₄ and C₁₆) was measured with it. 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 (*h*) is large and fixed. However, due to over-effect of *h* on viscosity calculation leads to water and hydrocarbons viscosity decrease as *h* decreases when micro-crevice thickness is small, which imply that because the effect of micro-crevice thickness, the viscosity calculated with these conventional methods deduced

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