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Effects of viscosity and sliding speed on boundary slippage in thin film hydrodynamic lubrication

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ABSTRACT

The paper presents an experimental study of the effects of two parameters: lubricant viscosity and sliding speed on boundary slippage in thin film hydrodynamic lubrication using a slider-on-disc tester. Two sets of experiments were purposely derived. One used the same types of lubricants of various viscosities with an oleophobic sliding surface. The other one adopted a base oil with additives of different concentrations of $C_6F_{13}COOH$, which provided different affinity to the surface. Viscosity effect was evaluated by the former, while the speed effect was illustrated from results of both tests. Lubricant film thickness was measured via optical interferometry under different speed/load conditions. A boundary yield stress slip model was adopted to construct film thickness-boundary yield stress charts for various running conditions. The boundary yield stresses corresponding to the measured film thickness under the specified running conditions were obtained from the specific chart. It was found that the boundary yield stress increased linearly with lubricant viscosity and sliding speed. The findings can be explained efficiently by the slip model proposed by Spikes and Granick in 2003 [1].

1. Introduction

The no-slip boundary condition at the solid/liquid interface has been applied extensively in fluid mechanics and lubrication analysis, although its validity has been doubted since the 19th century [2]. As detection techniques are improved, evidence for boundary slippage has been found both through direct measurements, e.g., particle image velocimetry (PIV) [3] and total internal reflection-fluorescence recovery after photobleaching (TIR-FRAP) [4,5], and indirect measurements, e.g., atomic force microscopy (AFM) [6,7] and surface force apparatus (SFA) [8,9].

The linear slip length model proposed by Navier [2] is widely adopted in physics because of its simplicity. Slip length is defined as the perpendicular distance from the solid/liquid interface to a point inside or beyond the solid wall at which the flow velocity is linearly extrapolated to zero. However, the boundary yield stress model (referred to as the limiting shear stress model in some references) is more popular in engineering [8,10]. The boundary yield stress model indicates that the onset of boundary slippage at the solid/liquid interface is governed by a yield stress value, and slip does not occur until shear stress at the interface reaches the yield value. Zhu and Granick [8] confirmed the existence of such yield stress by measuring the hydrodynamic force of Newtonian liquids on smooth surfaces with an oscillating SFA. Craig et al. [11] measured the hydrodynamic drainage force of sucrose solutions with AFM and proved that boundary slip would only occur when shear rate exceeds a threshold. From the observation of a stick-slip transition of surfactant solution flow through nanopores, Cheikh and Koper [12] found that the flow follows Navier-Stokes's equation using the no-slip boundary condition until the shear stress reaches a critical value.

Many experiments have been designed to evaluate the correlation between boundary slippage and working conditions, such as liquid molecule polarity [7], wettability [13], and surface roughness [14]. The effects of viscosity and shear rate have also attracted great attention, simply based on the concept that the boundary slippage is a response to the differences in the affinity of the liquid with the solid surface and the viscous force of the liquid flow. Fluid flow behaviors are largely governed by these two parameters: viscosity and shear rate, and it is of interest to understand how they might be related to the physical behavior at the interface. Craig et al. [11] observed from their AFM measurements of hydrodynamic drainage force that the slip length increased with the liquid viscosity. Priezjev and Troian [15] conducted molecular dynamics simulations (MDS) and also found that the slip length increased monotonically with the liquid viscosity (molecular

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Nomenclature

b	slip length defined in Navier slip length model
x	coordinate in direction of sliding
y	coordinate transverse to main direction of sliding
W	width of pad bearing (in the x direction)
L	length of pad bearing (in the y direction)
h	film thickness
h_o	film thickness at pad exit
p	fluid pressure
U	velocity of the glass disc in x direction
u_s	slip velocity at the solid/liquid interface in the x direction
v_s	slip velocity at the solid/liquid interface in the y direction
η	dynamic viscosity of lubricant
α	inclination of pad (in radian)
τ_b	shear stress at the solid/liquid interface under slip condition
τ_{xb}	shear stress at the solid/liquid interface in the x direction under slip condition
τ_{yb}	shear stress at the solid/liquid interface in the y direction under slip condition
τ_c	critical shear stress determining the onset of boundary slip
CA	contact angle
CAH	contact angle hysteresis

chain length). By contrast, Cho et al. [7] proved that no systematic dependence existed between the slip length and the liquid viscosity, although their measurement technique was the same as that employed in the work of Craig et al. [11]. Cottin-Bizonne et al. [9] made a similar conclusion that the flow boundary depends little on the liquid viscosity. They measured the viscous force induced by the drainage of water-glycerol mixtures of various viscosities confined between a sphere and a plane. Contradictory conclusions on the effect of shear rate on boundary slippage can also be found from different studies. Molecular dynamics simulations (MDS) of Thompson and Troian [16] illustrated the boundary conditions of a Newtonian liquid at the solid/liquid interface. They reported that the slip length was a constant at low shear rates. This finding is consistent with the Navier slip length model. However, slip occurs above a critical (high) shear rate, and the slip length increases rapidly with increasing shear rate. Craig et al. [11] demonstrated through direct measurement of the drainage force of aqueous Newtonian fluids with AFM that the slip length increased with the approaching velocity. The shear rate dependency was also concluded by Horn et al. [17], based on the squeezed-film drainage force measurements of a high molecular weight polymer solution made in a SFA. A strong shear dependence of the slip length was measured with a SFA by Zhu and Granick [8]. Similar to the findings in the MDS of Thompson and Troian [16], Zhu and Granick [8] also found that the onset of slip occurred when the shear rate was up to a critical value and beyond that, a strong shear-rate dependency was shown. Priezjev and Troian [15] also proved that the slip length exhibited a nonlinear increase with shear rate when a critical value for both shear thinning and Newtonian liquids was exceeded. Simultaneously, the independence of boundary slip from shear rate was also published. Cottin-Bizonne et al. [18] studied the boundary condition of Newtonian liquids on solid surfaces using a SFA and found that the slip length was constant and independent of the applied shear rate. This conclusion was later confirmed by Joseph and Tabeling [19] who observed the velocity profile of a water flow through microchannels by PIV and also reported that the slip length was independent of shear rate.

Inconsistent conclusions on the effects of liquid viscosity and shear rate were clearly obtained from the aforementioned works, which were largely based on MDS and flows between nano- or submicron-scale gaps e.g. AFM and SFA. This paper attempted to address the issue more from the engineering perspective. Experiments were designed in this study to obtain the effects of these two parameters on boundary slippage in thin film hydrodynamic lubrication.

2. Test rig and samples

A self-developed test rig that could realize a lubricating fixed-incline between a rotating glass disc and a stationary slider was employed in this study. Fig. 1 depicts the illustration of the setup. The inclination of the slider can be adjusted and fixed. Optical interferometry was adopted to measure the change in thickness of the lubricant (h_o in Fig. 1) sandwiched between the slider and the glass disc based on the variation of interference fringe order and intensity at a spot in the contact. A chromium layer with a 20% reflection rate, which was used as a beam splitter, was coated onto the glass disc to improve interference image quality. A protective SiO_2 layer with a thickness of 200 nm was coated on top of the chromium layer. Hence, the flow of lubricant is bounded by a stationary steel surface and a SiO_2 (glass) plane in the basic experimental set up. Film thickness was calculated from the recorded change in intensity at one arbitrary point during the acceleration or deceleration process. Additional details regarding the test rig and optical interference can be referred to [20].

The set of tests for the evaluation of the viscosity effect was conducted using an oleophobic slider. The lubricated surface of the steel slider was made oleophobic by applying a thin layer of EGC coating (supplied by SKF) to provide small and about the same adhesive strength with the oil samples. The size of the sliding surface was 4 mm (width, W)×9 mm (length, L). The roughness Ra of the EGC slider surface was 20 nm. To study the viscosity effect, two types of lubricants were prepared. The first type was glycerol solutions, which were prepared with five different concentrations of glycerol in order to provide a series of viscosity measurements. Three different polyalphaolefin (PAO) oils were also used in this study, namely, PAO 4, PAO 10, and a combination of 50% PAO 4% and 50% PAO 10 (by weight). The viscosities of all the applied lubricants are listed in Table 1. The contact angle (CA) and contact angle hysteresis (CAH) formed between the lubricants and the EGC surface were also measured and listed in Table 1 given that they reflect largely the intermolecular strength at the solid/liquid interface [13]. Apparently, the five glycerol solutions had roughly the same CA and CAH values. Such result is reasonable because these solutions have nearly the same chemical components. The three PAO oils presented also similar CA and CAH.

To detect the effect of the sliding speed on boundary slippage, specimen oils of the same viscosity and different adhesive strengths with the slider surface were prepared. Silicon oil 201–500 was chosen as the base oil. It was then formulated with additives of $C_6F_{13}COOH$ of different concentrations to provide oil samples of various adhesive

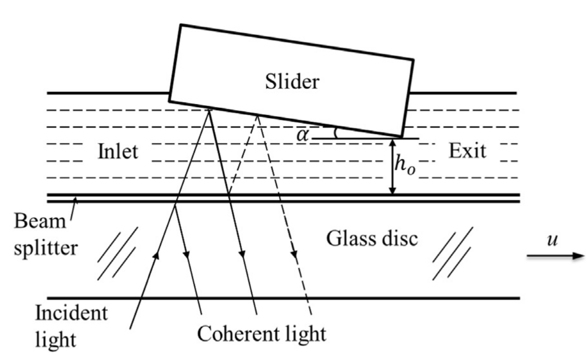

Fig. 1. Illustration of the fixed-incline test rig.