Slip length of the tribo system steel-polyalphaolefin-steel determined by a novel tribometer

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Abstract

Nowadays sealing systems are commonly designed by means of hydrodynamic and elastohydrodynamic theories. Although the analytical as well as the computational approaches have improved in meaning full manner since the last decades: For small sealing gaps, in the order of micrometers and below, a discrepancy between experimental investigated and theoretically predicted leakage flows occur. As a cause for the discrepancy a breakdown of the no slip boundary condition is suspected. Since in small sealing gaps the continuum hypothesis is violated and molecular effects have to be considered. One fundamental quantity to take molecular affects into account is the slip length.

Within this paper a new measurement apparatus to evaluate the slip length for hydraulic applications is presented. The adjustable gaps between two planar surfaces are in the order of magnitude of 1 µm. In a first step the slip length for the system steel-oil –steel is investigated at three different temperatures: $18\,^{\circ}\mathrm{C}, 22\,^{\circ}\mathrm{C}$ and $25\,^{\circ}\mathrm{C}$. The measured slip lengths are in the order of magnitude of ~100 nm.

KEYWORDS: Slip length, Tribology, Sealing Technologies

1. Introduction

Nowadays sealing systems are commonly designed by means of hydrodynamic and elastohydrodynamic theories. Although the analytical as well as the computational approaches have improved in meaning full manner since the last decades: For small sealing gaps, in the order of micrometers and below, a discrepancy between experimental investigated and theoretically predicted leakage flows occur. As a cause for the discrepancy a breakdown of the no slip boundary condition is suspected. Since in small sealing gaps the continuum hypothesis is violated and molecular effects have to be considered.

The discussion regarding boundary conditions at solid walls is as old as the momentum equations for Newtonian fluids itself. Already Navier /1/, as stated by Stokes /2/, suggested in his derivation of the Navier-Stokes equations a sliding coefficient close to the wall. Stokes /3/ himself favored the no slip boundary condition. His assumption was based on experimental investigations of du Buat /4/. Helmholtz /5/ suggested a linear boundary condition with a finite slip velocity u_s close to the wall. Slip velocity and shear rate $\dot{\gamma}$ are linked by the sliding coefficient λ called slip length:

$$u_s = \lambda\dot{\gamma}. \tag{1}$$

By Helmholtz's hypothesis the sliding coefficient or slip length has the dimension of a length and remains constant, for a respective sliding interface consisting of a fluid and a solid interface. Today Helmholtz's sliding coefficient is known as the slip length λ.

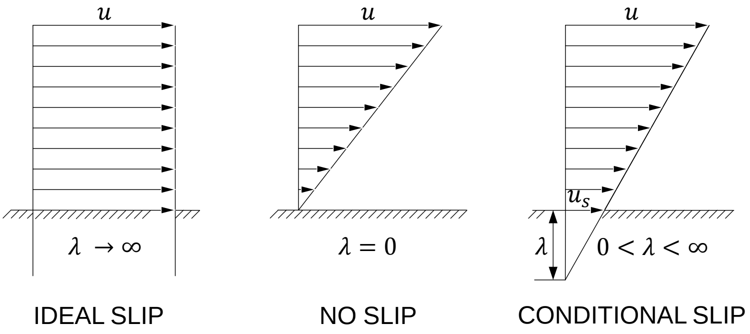


Figure 1: Boundary conditions in fluid mechanics.

In **Figure 1** are the common boundary conditions at solid walls presented: At first the ideal slip condition where the velocity u close to the solid wall and in the far field are identical. These boundary condition is commonly used if internal fluid friction is neglected. The second boundary condition is the no slip condition. Here the velocity at the wall is identical to the wall velocity. On the right hand side of Figure the conditional slip condition is constituted. The conditional slip condition and hence the slip length is key research subject of the current paper. At conditional slip the bulk fluid close to the solid wall moves relative to the wall, with the finite velocity u_s.Slip is often present at the interface of a gaseous and liquid fluid. At the interface of a fluid and a solid surface, slip is enhanced either by an electric double layer (**Figure 2** a) or by the adsorption of surfactants at the interface (Figure 2 b). The slip velocity u_s and the far field velocity u are linked by a linear velocity profile. The slip length λ describes the distance between the intersection point, of the wall perpendicular and the linear extrapolated velocity profile, and the distance to the wall. From geometrical point of view: The slip length represents an apparent enlargement of the flow regime normal to the main velocity flow.

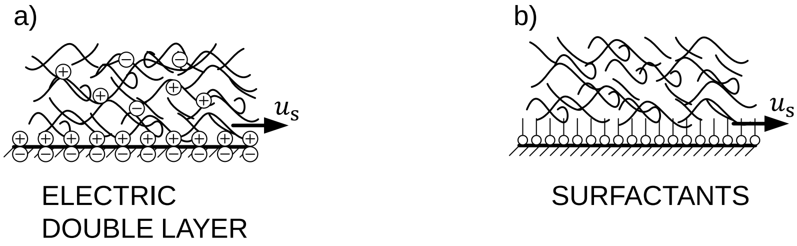


Figure 2: Slip at solid surfaces affected by an electric double layer or surfactants.

In the end of the 19th century the topic of wall boundary conditions was intensively discussed. The discussion was affected by various capillary measurements and Hagen-Poiseuilles equation published in 1846 /6/. Various studies either confirmed the no-slip condition or stated to have measured slip in the context of the measuring accuracy. The scientific discussion ends at the beginning of the 20th century with the result that, up to this time, if slip occurs its influence is too small to measure. Hence the no slip condition was assumed to be valid within a sufficient accuracy for technical applications. Since the mid of the 20th century the concept of no slip was accepted as textbook knowledge. Only a few authors e.g. Lamb /7/, a student of Stokes and Maxwell, and Goldstein /8/ remarked the concept of slip close to the solid wall. With improvements in processing capabilities, new experimental technologies and data acquisition measurements techniques to evaluate wall slip were developed since the 1970s. A review about experimental techniques, from the 1970s up to now, is given in Neto.et al. /9/.

Neto et al. /9/ distinguish four different techniques to measure the slip length: *1. Techniques tracing the fluid flow near a boundary, 2. Techniques based on force or* *displacement measurement, 3. Capillary techniques* and 4. *Quartz crystal resonators*. Roughly concluded the covered measurement techniques include six different measurement systems with numerous gradations and differences:

The tracer based methods consists of Particle Image Velocimetry (PIV) /10/, /11/, /12/, /13/ and Fluorescence Recovery after Photobleaching (FRAP) /14/, /15/, /16/, /17/, /18/, /19/, /20/. For the PIV technique Lumma et al. /12/ as well as Zettner & Yoda /13/ stated that they rather measured the slip between the tracer and the flow than the slip between the fluid and the solid wall. This statement is based on a dependency of the slip length of the used tracer particle size. With the FRAP technique Pit et al. /17/ measured for the system Hexadecane ($C_{16}H_{34}$) - solid sapphire surface modified by a stearic acid slip lengths from100 nm up to 350 nm. Hexadecane is one fluid in the covered literature that is approximately comparable with a hydraulic fluid. Other experimental investigations used commonly water solutions or long chained polymer melts as fluid. The expected slip length for the presented experiment are in the order of magnitude of 100 nm up to 1000 nm.

The methods based on force and displacement measurements consist of surface force apparatus (SFA) /21/, /22/, /23/, /24/ and the atomic force microscope (AFM) /25/, /26/. The key difference between both devices persist in the probe size. At the surface force apparatus, the probe has a diameter in the order of magnitude of millimeters. While the probe of the atomic force microscope (AFM) has a diameter of a few micrometers. The surface force apparatus was developed to measure the surface forces - introduced by van der Waals in 1879. The atomic force microscope was developed by IBM and Stanford University to resolve the molecular structure of insulator materials. The two other measurement devices are the capillary measurements and the quartz crystal resonators.

The existing apparatuses for slip length measurements use solid surfaces materials such as glass, silicon, mica or gold as materials. These surface materials are not of major importance in practical application of hydraulics. Today's available material combinations used to determine the slip lengths, are on the one hand a result of the development objectives of measuring equipment and on the other hand a result of the available manufacturing capabilities. Most available apparatus were designed for measurement tasks far beyond the slip length. PIV was developed for macroscopic flow field measurements. Surface force apparatus were designed to measure the van der Waals forces and the Atomic-force microscope was devised to resolve the molecular structure of insulator materials. Especially the last two measurement techniques based on force and displacement measurement require surface roughness within the molecular size (~1 Å=0.1 nm) and are across the scope of common mechanical capabilities. Another sticking point with respect to the restricted material pairings of individual measuring devices is that no comparable validation measurements were carried out so far between the individual apparatuses.

In this paper a new measurement technique is presented, to determine the slip length for hydraulic applications. The device was developed at the TU Darmstadt, at the Chair of Fluid Systems during the last years. The measurement is based on torque and displacement measurements. The sliding surfaces consist of steel and were prepared by the manufacturing process lapping. The fluid is a poly-alpha-olefin with a kinematic viscosity ν of 33 cSt.

The ongoing paper persists of five parts: At first the measurement principle is described. Followed by the detailed exposure of the test rig. On this basis the obtained results are presented. The paper closes with a discussion of the results and a conclusion.

2. Measurement Principle

In this chapter the measurement concept is presented to evaluate the slip length for a typical material system of the hydraulic. In **Figure 3** is the principle sketch of the measurement device illustrated.

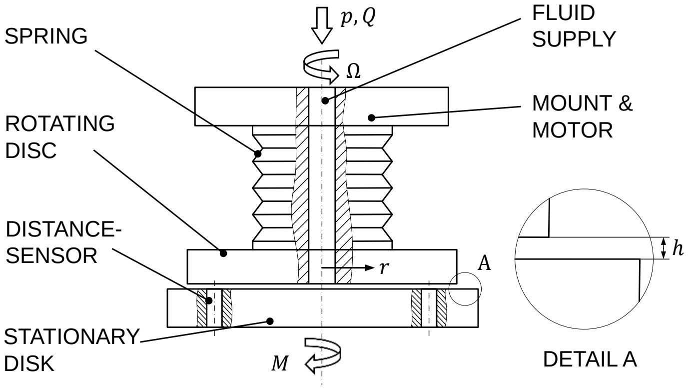


Figure 3: Measurement principle – Experimental setup.

The measurement principal was developed by Pelz in 2007 already published in /27/. Specified are the main parts of the concept: By the pressure p on the one hand the fluid is fored to a radial motion between the gap confining disks. On the other hand the two discs are separated in such a way that there is an equilibrium between the pressure and the spring fore at distance h. The gap distance is measured directly by two distance sensors located in the stationary disk. The torque transmitted by the fluid is also measured at the stationary disc.

In **Figure 4** the experimental examination of the slip length is represented. The transmitted torque is applied to the accompanying gap height. Measurements at a sufficient number of measurement points allow the determination of the torque at gap height $h = 0$ by extrapolation. The torque at $h = 0$ can not be measured due to the fact that each technical surface has a finite roughness $h > 2R_{\max}$.

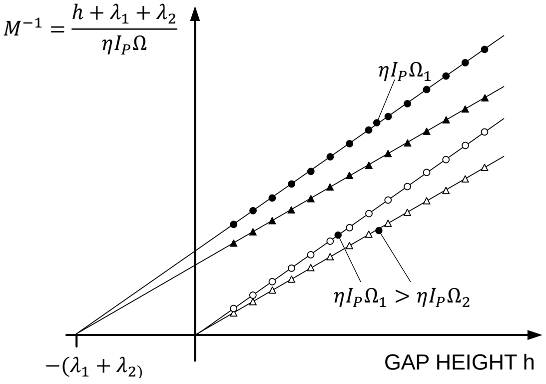


Figure 4: Measurement principle (Pelz)

From hydrodynamic lubrication theory it is known that the friction torque between two flat disks at distance h for no slip boundary condition is given by

$$M = \frac{\eta \Omega I_p}{h}. \tag{2}$$

η represents the dynamic viscosity, Ω the rotational speed of the disk and I_{p} the geometrical moment of inertia. From Equation 2 it can be figured out that the friction torque M is an inverse linear function of the gap height h. This relationship is illustrated in Figure 4 with the white filled markers. At infinitesimal small gap height the inverse friction torque tends to zero. With an increasing rotational speed of the rotating disk, the inclination of the linear function increases. The triangles and the circles denote two different rotational speeds at constant dynamic viscosity and equal geometry. Above it was mentioned that the slip length can be understood as an enlargement of the confined gap. For the presented test rig, slip occurs at the rotating as well as at the stationary disk. λ_1 represents the gap enlargement due to the surface at the stationary disk and λ_2 the enlargement due to the surface at the rotating disk. If the slip condition is considered in the friction torque, the inverse toruqe is given by

$$M^{-1} = \frac{h+\lambda_1+\lambda_2}{\eta\Omega I_p}. \tag{3}$$

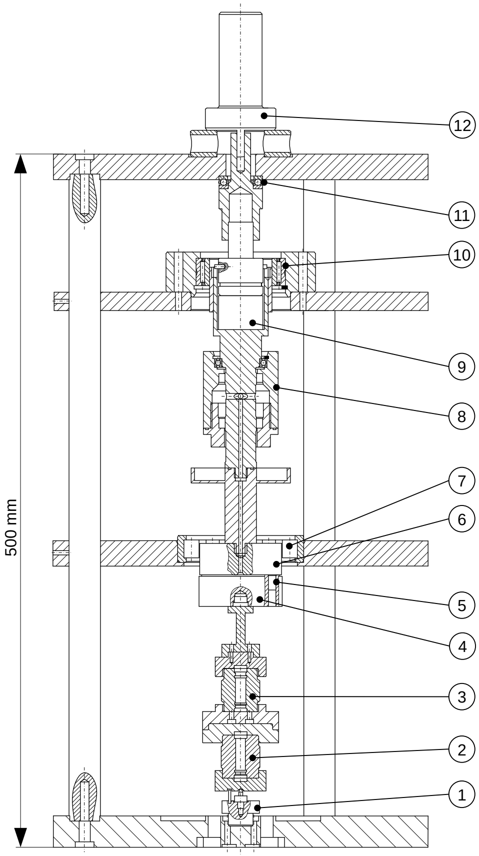
In the case of slippage at the confined surfaces, the friction torque at zero gap height is different from zero. This relationship is illustrated in Figure 4 by the black markers. The slip length can be figured out directly from the graph if the inverse moment is extrapolated up to the intersection with the horizontal axis. The negative gap height represents the apparent enlargement of the gap. The hypothesis that is based to Figure 4, is that the slip length is independent of the shear rate. This assumption was already published by Helmholtz /5/ and applies to check.

3. Test Rig

Figure 3 represents a principal sketch of the measurement device. In this section a detailed view on the design of the test rig will be given.

In **Figure 5** a sectional view of the test rig is represented. The main parts are named in the table below. For the function of the apparatus: The liquid enters the machine by a rotary feedthrough, passes per the drive train into the system and gets injected via the rotating disk. The gap height h is adjusted by the inlet pressure and the spring stiffness of the axial compliance. The axial compliance is achieved via a polyurethane spring. The axial force sensor is used to adjust the preload of the spring. The preloading is required to squeeze the fluid out of the gap to obtain gap heights in the order of micrometers. The torque is measured by a reaction torque sensor with an effective range of 1 Nm. The drive drain is beard by a fixed and a movable bearing. Due to the fact that each rolling bearing has a concentricity tolerance, which is too large to maintain a planarity of the rotating disk in the order of 100 nm, a compensation system is required. The toe bearing represents this compensation system. Due to the pressure within the confined gap, the stationary surface is always oriented planar to the rotating one.

Two capacitive sensors are inserted into the stationary disk. The used measurement system has a dynamic resolution of 1 nm. Due to the fact that at a vanishing gap distance the capacity of the sensors tends to infinity, the transmitter is caused to oscillate. To avoid electronic oscillations the sensors are located at a distinct difference behind the confining surface. The distance Δz by which the sensors are set back behind the surface was determined with a micro coordinate measuring microscope.



1	TOE BEARING	7	CYLINDRICAL ROLLER BEARING
2	FORCE SENOR	8	ROTARY FEEDTHROUGH
3	TORQUE SENSOR	9	SPRING
4	STATIONARY DISK	10	NEEDLE BEARING
5	DISTANCE SENSOR	11	DEEP GROOVE BALL THRUST BEARING
6	ROTATING DISK	12	MOTOR

Figure 5: TU Darmstadt slip length tribometer.

From **Figure 6** it can be figured out that the distance Δz is about 52.8 µm. Furthermore it can be seen that the surface seems to be very rough. In average surface roughness's were measured in the order of magnitude of 100 nm. From interference measurements it is known that the surface roughness is in the order of magnitude of 10 nm. Hence the inaccuracy is related to the micro coordinate measuring microscope. Due to the fact that the grip shifts during a measurement to create a planar measurement. The “surface roughness” represents nothing else than the bearing clearance of the linear guides of the measuring microscope. To obtain a more accurate measurement result for the reinstatement of the sensor surface a planar interference measurement will be conducted.

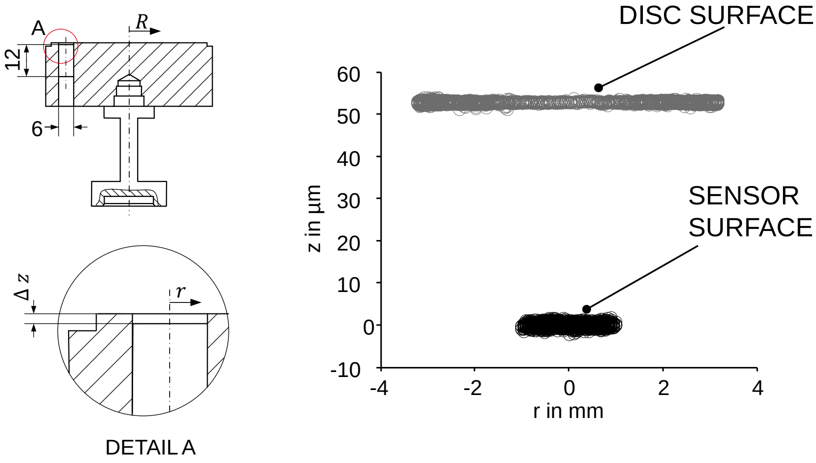


Figure 6: Reinstatement – distance sensor and solid surface**.**

4. Results

In this chapter the first results obtained with the previous described apparatus are presented.

In **Figure** 7 are slip length measurements at different temperatures presented. The measurements were conducted at a constant rotational speed of 60 rpm. The oil was a poly-alpha-olefin. The kinematic viscosity varied from $\nu_{20^\circ} \approx 72$ cSt down to $\nu_{30^\circ} \approx 45.5$ cSt. From Figure 7 emerges that the linear relationship between inverse torque and gap height (compare Figure 3) is properly measured. Furthermore the extrapolated inverse friction torque crosses the horizontal axes at a negative intercept. Hence a slip length is measured. The measured value is in-between the range of ~100 nm as expected. Up to now no absolute value is specified for the slip length. This has two reasons: On the one hand are the uncertainties of the reinstatement still too large. And on the other hand are the temperature uncertainties in one series of measurement not negligible.

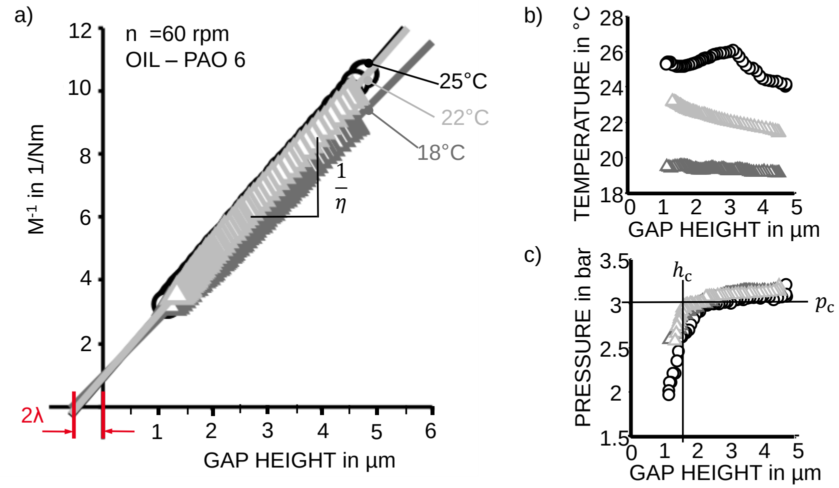


Figure 7: Slip length at different temperatures.

Figure 7 shows the positive perceptions of the new Tribometer. With the new measurement device the tribo-system is quantified three independent mentioned data: First the dynamic viscosity is given by the slope of the inverse friction torque in Figure 7 a), second the slip length λ is given by the intersection with the abscise and third a critical normal force is given by (p_c, h). At small gap height normal adhesion forces are present. The presented measurement device is sensitive to those forces.

5. Summary and Conclusion

Within this paper a new measurement apparatus to evaluate the slip length for hydraulic applications was presented. In a first step the measurement principle was presented. Based on this the design was exposed with the key constructive issues. In the measurement section slip length measurements at three different temperatures were presented. In the case of a temperature change of 10° C, the slip length varies in the order of 100 nm. As a result of temperature variations within a series of measurements, the slope changes are still uncertainty. Absolute values of the slip length are not yet quantified due to uncertainties with respect to the reinstatement of the distance sensor. But the results obtained so far are of the same order of magnitude as indicated in the literature.

The aim for the future is to reduce the uncertainties with respect to the absolute values of the slip length. Hence the reinstatement of the distance sensor will be measured using a planar interference technique. Due to this investigation method the accuracy will be improved by one order of magnitude. To keep the slope of the moment constant the apparatus will be used in temperature cabinet in future investigations. Based on these method the slip length for the material paring steel-oil-steel will be investigated at different temperatures and different shear rate.

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7. Nomenclature

d	Distance	m
h	Gap Height	m
I_p	Geometrical Moment of Inertia	m^4
M	Friction Torque	kgm^2/s^2
p	Pressure	kg/ms^2
u	Velocity	m/s
u_s	Slip Velocity	m/s
Δz	Reinstatement of the Distance Sensor	m
$\dot{\gamma}$	Shear Rate	1/s
η	Dynamic Viscosity	kg/ms
ν	Kinematic Viscosity	m^2/s