

Flow Measurements of a Polyphenyl Ether Oil in an Elastohydrodynamic Contact

Bénédicte Galmiche^a, Aleks Ponjavic^{a,b}, and Janet S. S. Wong^{*a}

^a Department of Mechanical Engineering, Imperial College London, UK SW7 2AZ. Fax: +44 20 7494 7023; Tel: +44 20 7594 8991; E-mail: j.wong@imperial.ac.uk.

^b Current address: Department of Chemistry, University of Cambridge, Cambridge, CB2 1EW, UK

* Corresponding author: j.wong@imperial.ac.uk

Abstract

A novel methodology, based on the use of phosphorescence imaging, is applied to determine the local through-thickness velocity profile of lubricant in an elastohydrodynamic (EHD) contact. The technique has spatial and temporal resolutions of 40 μm and 340 μs respectively and thus allows lubricant rheology to be investigated at conditions close to service conditions. The capability of the newly-developed method is verified by examining the flow of 5P4E polyphenyl ether, a lubricant base fluid used in very high temperature applications and well-known for its high viscosity-pressure coefficient. Experimental results highlight the effect of the contact pressure on the velocity profile of this fluid in lubricated contacts. At low pressures, the velocity profile of 5P4E is close to linear, characteristic of Couette flow. As the local pressure increases, its velocity profile progressively deviates from a Couette profile and shear banding is evident at high pressure.

Introduction

Elastohydrodynamic (EHD) lubrication is present in lubricated machine components that have mechanical parts that roll against one another, for example ball or roller bearings, cams and gears. In this lubrication regime, the lubricant film is subject to extremely high pressures, in the range of gigapascals, combined with shear rates that can reach up to 10⁸ s⁻¹. Under these conditions, liquid lubricants can exhibit properties very differently from those observed under ambient conditions and even low molecular weight organic liquids can be non-Newtonian.

Knowledge of the rheological behaviour of lubricants in EHD contacts is crucial for accurate prediction of friction, wear and fatigue life of engineering components. Although various models have been developed to describe the physical properties of lubricants in the very severe conditions present in EHD contacts [1–5], direct experimental validation is scarce. In particular, there is a lack of experimental data about the flow of lubricant between the two rubbing surfaces. It should be noted that

all predictions of friction coefficient and film thickness of lubricant films in EHD contacts rely on the assumption that the velocity profile of the lubricant film is linear. However, the very high pressure and high shear rate exerted on the lubricant film in an EHD contact casts doubt on the accuracy of this assumption. It is therefore important to measure directly the flow of lubricants in EHD contacts to improve the understanding and prediction capability of rheological behaviour of EHD lubricants.

Various techniques including interferometry [6, 7], ultrasonics [8, 9] and infrared emission [10, 11] have been used to measure experimentally the film thickness and temperature in EHD contacts. However, experimental measurements of velocity profiles in EHD contacts are more difficult due to the submicron thickness of the lubricant film, making the application of common velocimetry techniques, such as particle imaging velocimetry (PIV), unsuitable. For microscopic flows, molecular tagging velocimetry techniques (MTV) have proved useful in various applications, including the development of chemical and biological devices based on

the investigation of the flow in cylindrical microcapillaries [12] and the development of micronozzles for aerospace applications [13]. When a molecule in a flow is tagged in this setting, it can be identified within the rest of the fluid in the flow. The molecules constituting the flow can be tagged using a laser beam by photobleaching, phosphorescence or fluorescence [12, 14, 15]. The subsequent flow of tagged molecules can then be related to the flow of the fluid. In an EHD contact, MTV has been implemented to measure the average speed of lubricant flow [16]. Very recently, the authors have developed MTV based on fluorescence photobleaching and successfully obtained local flow profiles of lubricants in EHD contacts [17]. The effects of pressure [18] and surface chemistry [19] on flow profiles have been investigated with a spatial x- and y-resolution of 30 μm and 3 μm respectively and a temporal resolution of 30 ms.

The technique used in this work is a new molecular tagging velocimetry technique that supersedes the resolutions of the method previously developed in [17]. It allows investigation of the rheology of model, low viscosity lubricants at conditions much closer to those present in real machine components. Briefly, the new method, (molecular) Phosphorescence Imaging Velocimetry (mPIV), tags a small volume of fluid within an EHD contact using phosphorescence. The temporal evolution of the shape of the tagged volume is recorded. Then a numerical reconstruction scheme is used to iteratively deduce the unknown, through-thickness velocity profile.

The aim to this work is to demonstrate the capability of mPIV in obtaining through-thickness flow profiles in EHD contact at conditions and resolutions unattainable by other methods. The model lubricant used in this study is 5-phenyl-4-ether (5P4E). This synthetic fluid is employed in some aerospace applications due to its very high thermal and oxidative stability and has been widely used in EHD experimental studies

[20–25] because of its very strongly pressure-dependent viscosity. The flow curve for 5P4E, obtained with a pressurized Couette viscometer [26], shows a Newtonian regime at low shear rates with shear-thinning occurs at higher shear rates, followed by a constant shear stress regime that is characteristic of shear-banding. The present study applies mPIV to investigate the flow of 5P4E in an EHD contact. Complex flow phenomena are observed and shear-banding of 5P4E is evident in its through-thickness velocity profiles at high pressure conditions.

Experimental

Materials

The lubricant used in this study is commercial 5P4E (GBR Technology). The lubricant is doped with a phosphorescent dye, tris(dibenzoylmethane) mono(1,10-phenanthroline) europium(III) (Sigma-Aldrich) (referred to as *Eu dye* in this work), at a concentration of 1.8 mM. The complete dissolution of the dye in 5P4E is achieved by magnetic stirring for at least 2 hours at 60°C. At ambient conditions, 5P4E has a dynamic viscosity $\mu = 2.10 \text{ Pa}\cdot\text{s}$ and pressure-viscosity coefficient $\alpha = 45.9 \text{ GPa}^{-1}$ [27].

An EHD contact is created with a 19 mm borosilicate glass ball (PCS Instruments) loading against a glass slide (VWR). The arithmetic mean roughnesses (R_a) of ball and slide surfaces have been measured by a Talysurf profilometer (Form Talysurf Series 2) and an optical profilometer (Veeco, Wyko NT9100) and are 16 nm and 0.9 nm respectively. The applied normal load is varied from 1 to 17 N, leading to a maximum Hertzian pressure P_{max} between 140 and 360 MPa. A soft-EHD contact with low peak pressure $P_{max} = 232 \text{ kPa}$ was also obtained by loading a glass ball against a glass slide coated with a 1 mm layer of polydimethylsiloxane (PDMS) (Sylgard 184, Dow Corning). The glass ball rotates at a fixed peripheral speed of $U_b = 144 \text{ mm/s}$, while the slide remains stationary $U_d = 0$.

This gives an entrainment speed $U_e = (U_b + U_d)/2$ of 72 mm/s. The lubricant is contained on the slide by a PDMS well to ensure fully flooded conditions (see Figure 1). All experiments were carried out at room temperature.

The lubrication regimes for these operating conditions are identified in Esfahanian and Hamrock's map [28] as shown in Figure 2. Most conditions applied in this work lie in the piezoviscous-elastic (EHD) region, where extreme pressures and deformations are present. The exception is $P_{max} = 232$ kPa, it is in isoviscous-elastic (soft EHD) regime and has been used to validate the developed technique in a soft-EHD contact. Assuming isothermal condition, the pressure induced effects in the soft EHD contact are expected to be negligible, such that a Couette velocity profile is expected.

Phosphorescence imaging velocimetry

In this work, through-thickness velocity profiles are determined using phosphorescence imaging velocimetry (mPIV). Previously the authors have applied photobleached fluorescence imaging velocimetry (PFIV) [17] to obtain through-thickness velocity profile of polybutene (PB) in EHD contacts by tagging the fluorescently-doped PB using photobleaching. The main limitation of PFIV is temporal resolution. In PFIV, the tagged volume is observed as a low intensity volume against a bright background. Thus the requirement of a high relative photobleaching rate and the inherent low signal-to-noise ratio mean that only conditions of low entrainment speeds can be investigated. This in turn limits the choice of model lubricant to highly viscous lubricants and precludes the study of lubricant normally used in engineering practice. In the present study, a laser pulse is used to tag the phosphorescently-doped fluid; as such the tagged volume is bright due to phosphorescence emission. The velocity profile is then inferred by following the evolution of the shape of this tagged volume against a dark background. As only a short

laser pulse is needed to create the tagged volume, flow of low viscosity lubricants at higher speeds, as detailed in this study, can now be investigated.

The use of phosphorescence emission for velocimetry requires further discussion. Fluorescence and phosphorescence are both examples of photoluminescence. In both cases, light of short wavelength is absorbed and then re-emitted at a longer (less-energetic) wavelength. The relaxation of unstable excited electrons to the ground state can take multiple pathways. Emission of a photon from a singlet excited state to a singlet ground state, or between any two energy levels with the same spin, is called *fluorescence*. This process usually occurs on a timescale of nanoseconds to microseconds. In a *phosphorescent* process, excitation of electrons to a higher state is accompanied with the change of a spin state. Relaxation is then a slower process since it involves energy state transitions. Emission lifetimes in case of phosphorescent processes are in the range of microseconds to seconds. Both fluorescence and phosphorescence will be emitted by an excited molecule, with the former having much higher intensity than the latter. If phosphorescence emission is of interest, care must be taken to remove signal from fluorescence emission. In this study, this is done by incorporating a time delay between tagged volume creation and image acquisition. This time delay is longer than the fluorescence lifetime of the dye.

A schematic of the optical setup is presented in Figure 1. A 349 nm laser (Spectra Physics Explorer) operating at 1,000 Hz is used to create a phosphorescent column of lubricant within the contact. The laser beam is expanded onto the back of an objective (20× 0.5 NA). The full width at half maximum (FWHM) of the laser beam on the focal plane of the objective is deduced from the image of a focused phosphorescent spot created in a thin film of doped lubricant and is about 10 μm. A tagged volume is generated by exposing the phosphorescently-doped lubricant to a short

laser pulse (FWHM < 5 ns). The tagged volume can be considered as a through-thickness cylinder with uniform cross-sectional area and intensity. The uniformity of the cross-section of the tagged column through the film thickness is verified in the next section (see Figure 5).

The phosphorescence emission from the tagged column is then collected through the objective and passes through a 488 nm long pass filter to remove the residual signal from the laser. Images of the shape evolution of the tagged column against time are recorded in the x-y plane using an intensified CCD camera (Hamamatsu Orca-R²).

A first image is recorded 2 μ s after the laser pulse excitation. The 2 μ s delay was determined to be sufficient to ensure that only phosphorescence emission from the tagged volume will be collected. Then a sequence of 17 images is recorded with an exposure time of 5 μ s. The exposure time is sufficiently small compared to the speed at which the phosphorescent volume is travelling to avoid blurring of images (the distance that the tagged column travels during a frame is actually smaller than a pixel). There is a delay of 20 μ s between consecutive images. Hence the observation time for each image sequence is 342 μ s. Image sequences obtained directly from the experiment without any correction are referred as raw sequences.

Flow profile determination

Raw sequences contain phosphorescence signals from the Eu dye in the doped lubricant and also, potentially, from background phosphorescence of rubbing surfaces and 5P4E itself, I_b . I_b is captured by obtaining sequences of 20 images with non-doped 5P4E in identical conditions. It is about 5% of the total signal collected and has a lifetime of about 14 μ s. The background phosphorescence sequence (Figure 3 (b)) is then subtracted from the raw sequence (Figure 3 (a)) to give the background corrected sequence (see Figure 3 (b)). As I_b is low, the difference between

raw sequences and background corrected sequences is small (see Figure 3 (a) and (c)).

The phosphorescence lifetime of a dye is affected by experimental conditions, such as its solvent, pressure and temperature. The lifetime of Eu dye in 5P4E in an EHD contact has been inferred from the integration of the temporal intensity distribution at room temperature. It decreases from about 110 μ s to 10 μ s for peak pressure P_{max} from 151 MPa to 313 MPa. Note that the phosphorescence lifetime of the glass sphere and glass slide is much shorter than the phosphorescence lifetime of the Eu dye in 5P4E at low pressure.

Each background-corrected image of a sequence is normalised by its total intensity to eliminate the temporal decrease of phosphorescence. This gives the normalised sequence and is used to obtain through-thickness velocity profiles $u(z/h)$. An iterative reconstruction scheme similar to one detailed in [17] is used to determine $u(z/h)$ from the spatiotemporal intensity distribution in the x-direction, averaged in the y-direction over 5 pixels. The reconstruction is complete when the simulated spatiotemporal intensity distribution from the reconstructed $u(z/h)$ matches the experimental spatiotemporal intensity distribution.

The determination of through-thickness flow profile assumes that a through thickness tagged volume is created and is cylindrical (while the intensity distribution is Gaussian). Hence, assuming negligible side flow at the centre of the contact, the width of the stretched tagged volume (in the y-direction) should remain constant irrespective of x position. In order to check the uniformity of the cross-section of the tagged volumes within the film thickness created in this study, intensity profiles along the y-direction have been determined from the normalised background corrected image recorded 302 μ s after the laser pulse at different positions (A), (B) and (C) along the x-direction under Couette flow

conditions (Figure 4 (a)). This corresponds to the lowest pressure case in this study. Figure 5 shows that the geometry (both width and shape) of the intensity distribution of the tagged volume along the y-direction does not vary with x-position. Hence the cross-section of the initial tagged column of fluid is uniform within the film thickness (i.e. in the z-direction). In addition, U_b and U_d determined from the flow profile (Figure 4 (c)) based on Figure 4 (a) match the actual applied speeds (i.e. $u/U_b = 1$ and 0 at $z/h = 1$ and 0 respectively), confirming that a through-thickness cylinder is created between the glass slide and the glass ball even under the conditions that give the thickest lubricant film investigated in this work.

The spatial resolution of this technique in the x-direction is governed by the size of the initial phosphorescence spot as the tagged column has to travel at least a distance which is equivalent to its own size during the acquisition of the images for the determination of the velocity profile. While the FWHM of the phosphorescence spot is 10 μm , the distance travelled by the spot and hence the resolution in x-direction are set at approximately 40 μm . The required acquisition time is about 340 μs . It depends on test speed and reduces with increasing test speed. The spatial resolution in the y-direction is about 2 μm due to the averaging of the intensity profile over 5 pixels. The resolution in the z-direction is governed by several factors including the roughness of the surfaces and the reconstruction scheme. It has been shown in [29] that the reconstruction scheme resolves the velocity profile to within 10 % of the film thickness, due to the limitation of resolvable relative shear rates. Since the thickness of lubricant films investigated in the present study is larger than roughness of rubbing surfaces, the restrictive factor is here the limitation of the reconstruction scheme.

How the spatial resolution compares with the contact diameter requires special attention. Since normal pressure within an

EHD contact resembles the Hertzian contact pressure distribution, the normal pressure exerted onto the lubricant is position dependent and lubricant flow may differ locally. This consideration is especially critical in piezoviscous conditions. As the obtained profile represents the average flow of lubricant within the measurement distance, the effect of averaging will depend on the rate of change of pressure with respect to x-position $\frac{dP}{dx}$. As $\frac{dP}{dx}$ diminishes as we move closer to the centre of the contact, so does the effect of averaging. $\frac{dP}{dx}$ around the centre also diminishes as the applied pressure and hence the contact area increases.

In this study, through-thickness velocity profiles have been investigated at the centre of the contact, meaning that the tagged column of lubricant travels from position $x = 0 \mu\text{m}$ to $x = 40 \mu\text{m}$ during the acquisition of the images needed in the fit algorithm. To estimate the effect of averaging at various loading conditions, the size of the contact area has been measured using laser induced fluorescence (LIF) [30]. The measured contact diameters for peak pressures in the piezoviscous-elastic regime are in good agreement with approximated theoretical calculations using Hertzian contact mechanics [31] and are 165 μm and 293 μm for the peak pressures 201 MPa and 362 MPa respectively in a glass/glass contact. Within this distance, the variation in the local pressure is about 12 % for the lowest pressure investigated at $P_{max} = 201 \text{ MPa}$ and drops to 4 % for $P_{max} = 362 \text{ MPa}$. Hence the x-resolution is sufficient at high pressure to determine reliable velocity profiles in shear banding conditions. When the pressures decrease the viscosity of 5P4E becomes less and less sensitive to pressure. Thus the 12 % local variation in pressure within the measurement distance for $P_{max} = 201 \text{ MPa}$ is unlikely to affect significantly the velocity profile.

The x-resolution can be improved by using higher numerical aperture objective, which

would make the diameter of the initial phosphorescent spot smaller and would therefore reduce the distance needed to completely distinguish two spots when shear banding occurs.

Results and discussion

The low pressure contact with $P_{max} = 232$ kPa corresponds to the case of a soft EHD where pressure effect is small and a Couette flow profile is expected. The normalised background-corrected image sequence (Figure 4 (a)) shows that the tagged volume is stretched in the x-direction with time. Based on Figure 4 (a), the averaged intensity distribution over 5 pixels in the y-direction is shown in Figure 4 (b) (circles). The averaged intensity distribution is used to determine the lubricant's flow profile (Figure 4 (c)) and a Couette flow profile with stick boundary condition is indeed obtained. The numerical intensity distribution (Figure 4 (b) (lines)) based on the determined flow profile matches the experimental results (Figure 4 (b) (circles)) well (with an average goodness of fit $R^2 = 0.99$). This shows that the newly-developed phosphorescence-based technique is capable of determining through-thickness flow profile accurately at high entrainment speed, which is at least 2 orders of magnitude higher than our previous work. This capability is crucial for the future study of low viscosity lubricant.

Results presented hereafter focuses on the behaviour of 5P4E under piezoviscous conditions. They are obtained at the centre of the contact ($x = 0$ and $y = 0$). Central film thickness, h , of 5P4E was measured at various pressure by laser induced fluorescence (LIF) [30] and ranges from $1.2 \mu\text{m}$ to $1 \mu\text{m}$ for peak pressures between 201 MPa and 362 MPa. This corresponds to average shear rates at the centre of the contact $\dot{\gamma} = U_b/h$ ranging from $1.2 \times 10^5 \text{ s}^{-1}$ to $1.5 \times 10^5 \text{ s}^{-1}$.

Phosphorescence images (Figure 6 (a)) show that at 255 MPa, the tagged volume evolves from one circular spot ($\Delta t = 22 \mu\text{s}$) to two spots of different intensities ($\Delta t =$

$302 \mu\text{s}$). This observation suggests that 5P4E at the centre of the EHD contact consists of two layers flowing with very different speeds. The reconstructed velocity profile presented in Figure 6 (c) shows that the profiles can be divided into regions of different slopes. This is an interesting observation. Recall the data presented in this work was obtained where contact pressure is maximum. At this position $\frac{\partial P}{\partial x}$ is zero, consequently through-thickness shear stress is constant. It then follows that any change in the slope of the flow profile, which represents a change in local shear rate $\dot{\gamma}(z)$ must be accompanied by a change in local viscosity $\mu(z)$. Hence, observed deviation from a linear velocity profile as shown in Figure 6 (c) can therefore be attributed to a through-thickness variation of 5P4E viscosity.

Three regions can be identified in Figure 6 (c). The upper highly viscous (with slope tends to infinity) boundary region travels at a speed similar to that of the ball while the bottom boundary layer has a profile that resembles Couette flow. The two boundary layers are separated by a localised, highly sheared layer ($\frac{z}{h} = 0.2$ to 0.4) of low viscosity. This indicates that 5P4E exhibits inhomogeneous shear or shear banding behaviour where the region with the lowest viscosity will show the highest shear rate. Note, the reconstruction scheme could only determine relative shear rates up to about 3.5 [29]. Hence the profile shown may have underestimated the shear rate at localised shear flow region.

The change from Couette flow to shear banding due to pressure is gradual, as shown in Figure 7. When the contact pressure increases, the flow progressively deviates from a Couette flow with increasing amount of fluid travelling at the same speed at the ball, i.e. an upper viscous boundary layer grows with increasing pressure. Thus, the transition between a pure Couette flow and a shear-banded flow takes place through changes in the velocity profile in the upper part of the film. The remaining lower part of

the film follows a roughly linear flow profile with increasing shear rate. As pressure increases further, shear banding appears. Central transition region of high shear rate becomes more localised as pressure increases. Shear banding in 5P4E is fully developed at the highest pressures investigated in this work. The observation of an asymmetric flow profile is consistent with [32] where 5P4E is seen to be divided into two layers of different thickness in an EHD contact. The three types of 5P4E flow profiles observed are summarised schematically in Figure 8.

Both the shape of the flow profile and the position of the highly sheared region are affected by the applied pressure, as shown in Figure 7 and Figure 8. While a pressure-induced transition from Couette flow to non-linear flow profile has been observed in polybutene (PB) [18], PB gives a flow profile which has been described as partial plug flow, i.e. the two boundary layers have low viscosity and experience high shear rate while the centre of the fluid flows like a plug. Hence 5P4E behaves very differently to PB, with the growth of the upper viscous boundary layer forming next to the moving surface as pressure increases. Such difference may stem from their rheological sensitivity to pressure and temperature. The increase in applied shear rate in this work as compared to the conditions applied to PB can also affect the flow of lubricant.

Shear-banding of 5P4E at high pressure has been previously observed by Bair et al. [33, 34] using flow birefringence in a high-pressure flow visualization cell where the deformation behaviour of 5P4E was investigated within a shearing gap of several tens of micrometres. The transition from linear Newtonian behaviour to rate-independent behaviour has also been illustrated by flow curves in [26, 34] obtained using a pressurized Couette viscometer. A Newtonian regime has been observed at low shear rates, followed by a shear thinning region and then by a limiting shear stress region. In fact shear banding behaviour has been attributed to the

existence of a limiting shear stress at which the response becomes strain-rate independent [23]. In [34], a constant limiting shear stress region has been found to appear at shear rates higher than about $3,000 \text{ s}^{-1}$ for the following conditions: $P = 0.11 \text{ GPa}$ and $T = 20^\circ\text{C}$. Hence shear banding of 5P4E may occur at pressures typical of EHD contacts. Note similar conditions have been applied in this work although higher shear rates have been achieved. To find out if our test conditions have reached the limiting shear stress region, estimation based on 5P4E traction map in Evans and Johnson [35] has been used to identify the rheological regime our experiments correspond to. The test conditions applied lie in either the Eyring regime or viscoelastic regime. Due to the shear rate applied, the Eyring equation as shown in equation (1),

$$\dot{\gamma} = \frac{\sigma_0}{\mu(P, T)} \sinh\left(\frac{\sigma}{\sigma_0}\right) \quad (1)$$

where $\dot{\gamma}$ is shear rate, σ is shear stress and σ_0 is the Eyring stress of the fluid, can be applied to both regimes. This suggests that shearing banding of 5P4E observed in this work occurs before a limiting shear stress is reached. This would be possible when a fluid with temperature and/or pressure sensitive viscosity is used as such through-thickness temperature/pressure variation can give rise to viscosity heterogeneity for shear localisation. A true limiting, shear rate independent, shear stress regime can only be achieved if 5P4E actually ‘breaks’. This is referred as mechanical shear banding [26].

Through-thickness viscosity variation can be temperature induced. If a thermal gradient does exist, the moving ball would be cooler than the stationary surface. Thus the very viscous boundary layers of lubricant formed close to both surfaces at high pressure may potentially be due to thermal effects. To investigate if temperature gradient is responsible for the observed shear banding in 5P4E, estimations of the rise in temperature due frictional heating of the film itself and of both stationary and moving surfaces have been respectively performed

660 using the approach of Olver et al. [5] and
 665 P_{max} = 176 MPa and increases to 70°C for
 P_{max} = 362 MPa. The average temperature
 rise in 5P4E film is however only about 2°C
 above the surface temperature in all cases.
 This suggests that the existence of through
 670 thickness thermal gradient in the film is
 unlikely.

While through thickness thermal gradient
 may be small in the 5P4E film, the film is
 nevertheless warm. The glass transition
 675 pressure of 5P4E would increase from 200
 MPa in ambient temperature to 400 MPa at
 70°C, and reaches 600 MPa at 90°C under
 static conditions [37]. The applied P_{max} =
 362 MPa would thus be insufficient to
 680 induce 5P4E to undergo glass transition in
 our applied test conditions. This supports
 that the shear bands observed are not
 mechanical shear bands.

The application of shear in an EHD contact
 685 can promote alignment of 5P4E with the
 degree of alignment increases with
 increasing test speed [38, 39]. Alignment of
 5P4E can reduce its viscosity. Partial
 alignment can potentially occur if a thermal
 690 gradient exists, giving rise to viscosity
 heterogeneity in the film [40]. Further work
 is on the way to explore this possibility.

While the temperature of 5P4E film in the
 contact increases with pressure, the shear
 695 banding becomes more localised. The
 evolution of 5P4E profiles suggests that a
 very viscous layer form initially at the top,
 moving surface. This layer grows into the
 remaining of the lubricant towards the lower
 700 surface. The remaining fluid obeys Couette
 flow despite experiencing increasing shear
 rate due to the formation of thicker upper
 boundary layer with pressure. The origin of
 such pressure dependence is currently
 705 unclear. Since the shape of the film is
 governed by the applied normal stress, it is
 likely that this in turn affects the through-
 thickness stress distributions within 5P4E.

As 5P4E has a high pressure-viscosity
 710 coefficient, small variation of pressure
 distribution can greatly affect viscosity
 distribution in the film, resulting in the
 observed dependence.

Conclusion

715 For the first time, through thickness velocity
 profiles in an EHD contact at high speed
 have been obtained by phosphorescence
 imaging. The developed technique
 supersedes a previous technique based on
 720 fluorescence photobleaching and has
 allowed investigation of flow property of
 lower viscosity lubricants at conditions
 closer to actual service conditions than our
 previous work. The technique has been
 725 validated for a lubricant film of 5P4E under
 Couette flow obtained at low pressure and
 then applied to high pressure contacts. The
 latter shows clearly the development of
 shear localisation in 5P4E as the contact
 730 pressure increases. This emphasizes that
 linear velocity profile cannot be assumed in
 models for predicting friction and wear in
 engineering applications.

Since pressure affects the velocity profile of
 735 5P4E in an EHD contact, it is likely that the
 velocity profile of 5P4E changes as 5P4E
 travels across the contact due to EHD
 pressure distribution. Thus further
 investigations will consist of determining
 740 both film thickness profiles and velocity
 profiles within the contact area from inlet to
 outlet. Also, as the film thickness has been
 shown to depend on the slide-to-roll ratio
 [41], further work will focus on the effect of
 745 the slide-to-roll ratio on the velocity profiles
 and the shear banding behaviour of 5P4E in
 EHD contacts.

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Figures

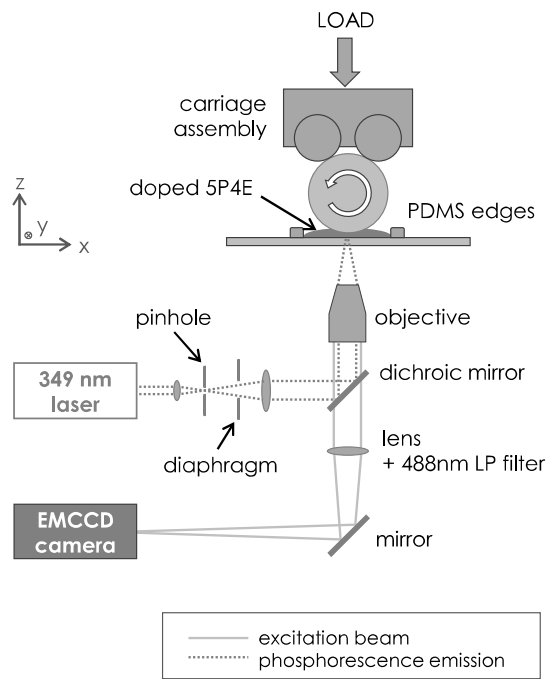


Figure 1. Schematic of the phosphorescence imaging setup

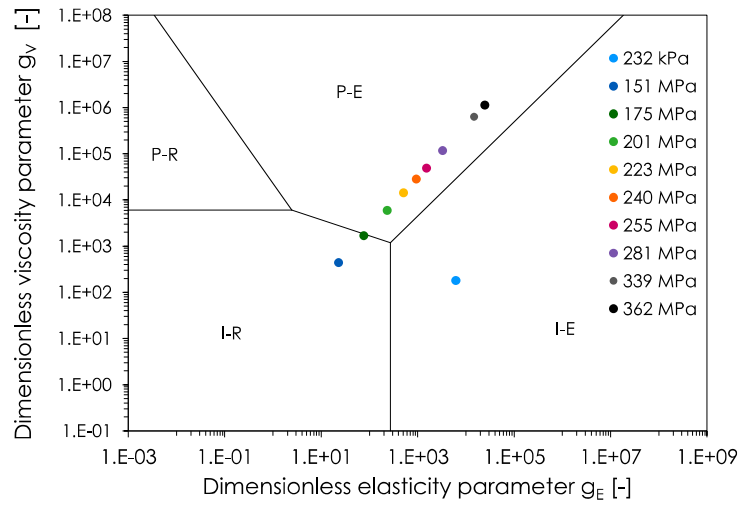


Figure 2. Lubrication map constructed for a circular contact ($U_e = 72$ mm/s). I-R: isoviscous-rigid, P-R: piezoviscous rigid, I-E: isoviscous-elastic, P-E: piezoviscous-elastic regime. The symbols represent the operating conditions for various peak pressures investigated in the present study.

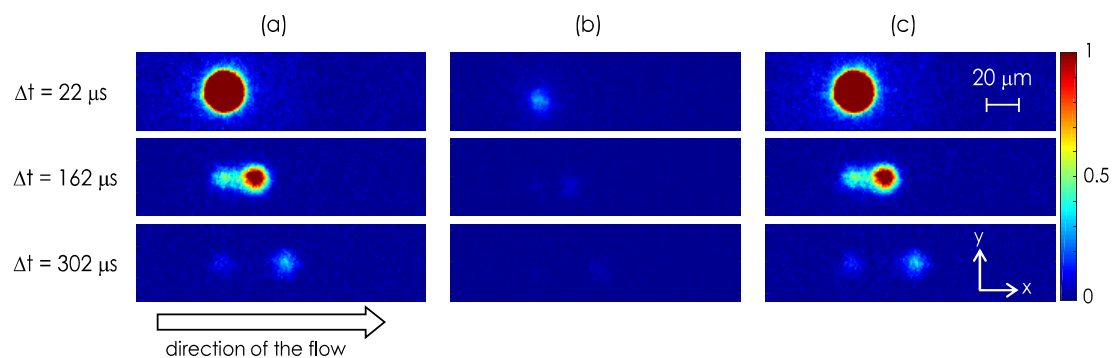


Figure 3. (a) Examples of raw images; (b) background phosphorescence images; and (c) background corrected images at different delays Δt after the laser pulse. The colour scale is similar in all cases and is deliberately saturated at high levels to enhance the background phosphorescence. These images are obtained for the contact pressure $P_{max} = 255$ MPa and the ball speed $U_b = 144$ mm/s.

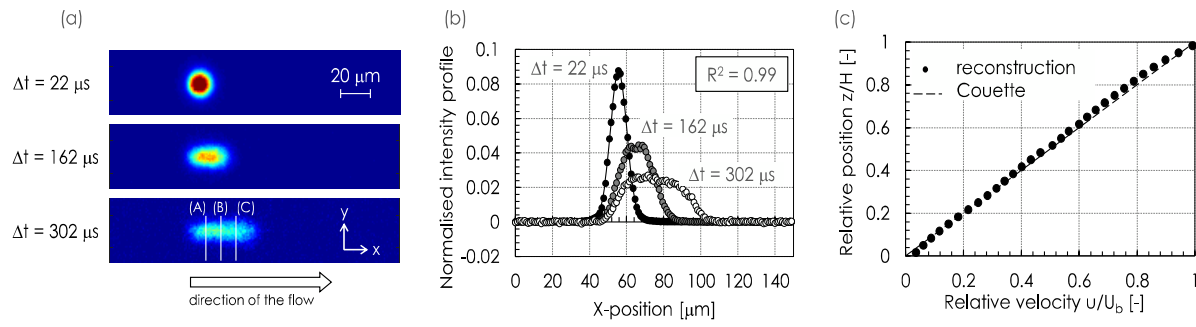


Figure 4. Phosphorescence Imaging Velocimetry results for the contact pressure $P_{\text{max}} = 232 \text{ kPa}$, and the ball speed $U_b = 144 \text{ mm/s}$. (a) Normalised background corrected images (b) Averaged experimental (circles) and numerical (lines) intensity distributions. (c) Reconstructed (circles) and Couette (dashed lines) velocity profiles.

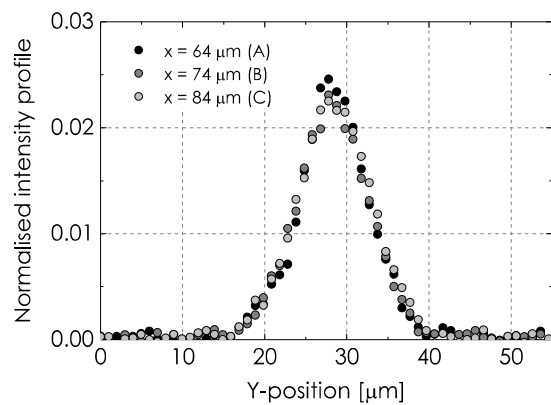


Figure 5. Intensity profiles along the y-direction determined at different x-positions in a Couette flow at $\Delta t = 302 \mu s$ (see Figure 4 (a)). (A) $x = 64 \mu m$, (B) $x = 74 \mu m$ and (C) $x = 84 \mu m$.

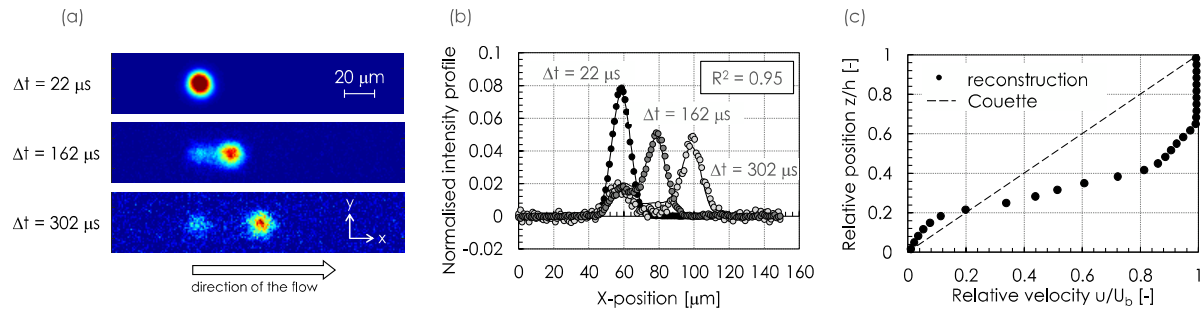


Figure 6. Phosphorescence Imaging Velocimetry results for the contact pressure $P_{max} = 255 \text{ MPa}$, and the ball speed $U_b = 144 \text{ mm/s}$. (a) Normalised background corrected images (b) Averaged experimental (circles) and numerical (lines) intensity distributions. (c) Reconstructed (circles) and Couette (dashed lines) velocity profiles.

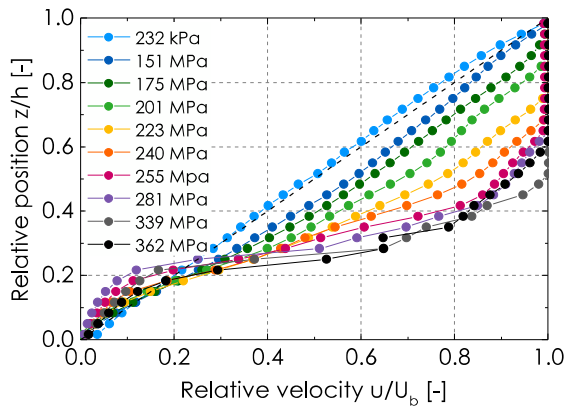


Figure 7. Reconstructed velocity profiles at different contact pressures ($U_e = 72$ mm/s) (dashed line correspond to a theoretical Couette flow)

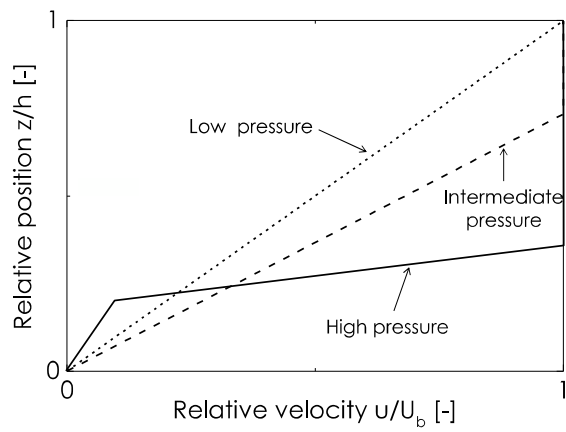


Figure 8. Three types of flow profiles of 5P4E observed in an EHD contact