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An Experimental Study of Elastohydrodynamic Central and Minimum Film Thicknesses for Various Material Parameters

Abstract

A newly developed experimental technique, based on colorimetric interferometry, has allowed accurate measurement of central and minimum elastohydrodynamic (EHD) film thickness for a wide range of operating conditions. This study was aimed at determining the influence of various material parameters on central and minimum EHD film thicknesses. Obtained experimental data were compared with Hamrock and Dowson film thickness equations and a numerical solution presented by Venner. The results obtained confirmed that the ratio between the central and minimum film thicknesses changes significantly with both load and material parameters.

Keywords: colorimetric interferometry, elastohydrodynamic lubrication, central and minimum film thicknesses, Hamrock and Dowson, Venner

INTRODUCTION

The ability to estimate film thickness in lubricated contacts is one of the most important practical aspects of the investigation of elastohydrodynamic (EHD) lubrication, because the EHD film may influence not only the contact fatigue life of the rubbing surfaces, but also their wear and scuffing failure. EHD film thickness behaviour is obviously related to friction and subsequently energy losses within the contact.

EHD lubrication is most frequently defined as a form of hydrodynamic lubrication where elastic deformations of the rubbing surfaces are significant. Hydrodynamic lubrication film thickness is a function of normal applied load, velocity of the surface, lubricant viscosity and contact geometry. The same parameters are used for the calculation of EHD film thickness, but with the addition of the effective elastic modulus and the pressure–viscosity coefficient of the lubricant.

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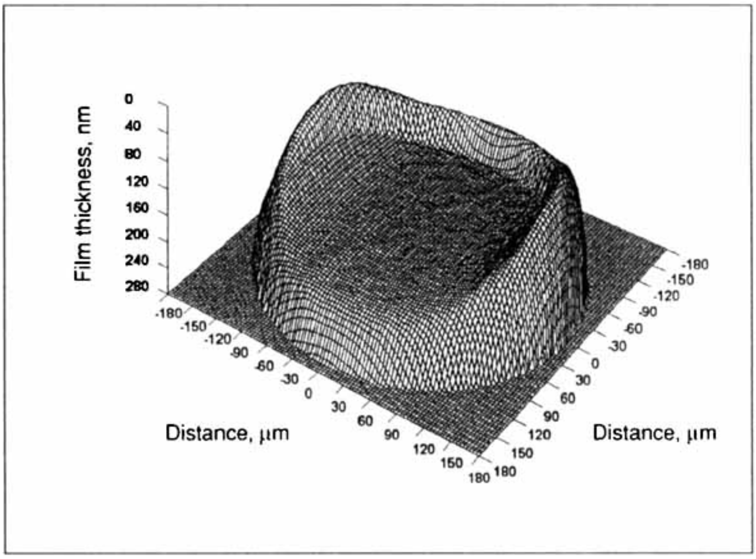
There are several widely used equations for estimating both the central and the minimum EHD film thickness. The most widely accepted equations for a fully flooded, isothermal EHD elliptical contact, are those established by Hamrock and Dowson,[1] in which the film thickness varies with the ellipticity, speed, load, and materials parameters. These equations are useful not only for design purposes but also for understanding the influence of various parameters on EHD film thickness. They show that film thickness is primarily a function of the speed and materials parameters, but is relatively insensitive to load.

One of the major limitations of most film thickness equations is that they have been derived by a least-squares fit of the data obtained from numerical solutions, covering only a certain range of operating conditions. For example, the Hamrock and Dowson minimum and central film thickness equations were obtained by considering thirty-four cases that included situations equivalent to using rubbing surfaces made of bronze, steel, and silicon nitride, and with paraffinic and naphthenic mineral oils as lubricants.

During the last twenty years several experimental attempts have been made to validate these equations. Gohar[2] employed several types of contacting materials, that included a combination of perspex, glass and sapphire discs, and steel and tungsten carbide balls, and reached a maximum contact pressure of 3.5 GPa. He found the ratio between the minimum and central film thicknesses to be between 0.5 and 0.75. Koy and Winer[3] measured minimum film thickness in an EHD point contact between a sapphire disc and steel rollers, in order to evaluate the Hamrock and Dowson minimum film thickness formula for the ellipticity parameter from 0.117 to 3.7. They found measured minimum film thickness to be about 30% greater than that predicted by the film thickness formula. Their conclusion, that the Hamrock and Dowson minimum film thickness formula conservatively predicts the minimum film thickness in EHD contacts, with adequate accuracy, was supported by the work of Dalmaz and Chaomleffel.[4] They measured the minimum and central film thicknesses in rolling point EHD contacts for six lubricants, and observed a good correlation between the Hamrock and Dowson film thickness formulae and experimental data for the dimensionless materials parameter lower than 10^4. Above this value, the Hamrock

Figure 1 Three-dimensional EHD film thickness distribution obtained by colorimetric interferometry



and Dowson equation was found to underestimate measured minimum film thickness by 20 to 50%. Nevertheless, all the above-mentioned results were obtained using conventional optical interferometry, which is what limited their ability to measure minimum film thickness accurately for a wider range of operating conditions.

In the early 1990s, the wider availability of digital image processing equipment brought about the development of new techniques for the evaluation of chromatic interferograms. Gustafsson *et al.*[5] were the first to use colour image processing for lubricant film shape determination. They compared hue values from digitised interferograms with calibration values obtained with known geometric shapes. This technique is suitable for EHD film thickness mapping within the range 95–700 nm with high spatial resolution, but some starting point must be set for determination of the absolute film thickness values. Recently, Cann *et al.*[6] modified this technique for film thickness shape measurement within the range 0–150 nm with the help of a spacer layer, and Smeeth and Spikes[7] presented a modification of ultra-thin film interferometry that enabled them to obtain, for the first time, accurate central and minimum EHD film thickness measurements at high pressures.

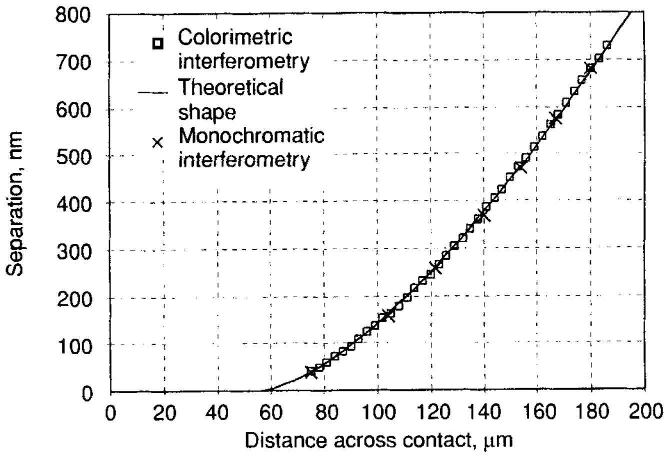


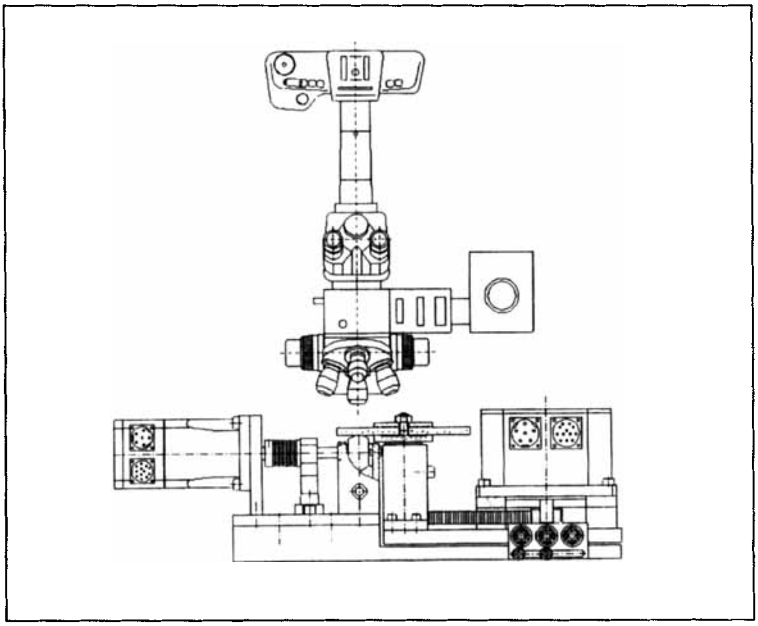
Figure 2 Experimental surface deformation profile taken across one half of a static contact and its comparison with calculated Hertzian profile

Recently, we reported on an experimental technique for the precise determination of lubricant film thickness distribution in EHD contacts based on colorimetric interferometry.[8] This technique successfully overcomes the limitations of conventional optical interferometry, and has turned out to be an effective tool for simultaneous determination of both central and minimum film thicknesses. As such, it has been used in the present study to clarify the influence of the dimensional materials parameter on central and minimum film thickness.

EXPERIMENTAL TECHNIQUE AND MATERIALS: Experimental technique

In this study, a new experimental technique has been employed for the determination of central and minimum film thicknesses. This technique, based on colorimetric interferometry, combines conventional chromatic interferometry with image processing and differential colorimetry, and allows us to obtain detailed information on EHD film thickness and shape (**Figure 1**). The lubricant film thickness is determined by comparing L* (psychometric lightness), a* (redness–greenness), b* (yellowness–blueness) colour coordinates between a digital colour chart and a digitised EHD interferogram with the help of the CIE 1976 L*a*b* colour-difference equation. The digital colour chart contains values for L*, a*, b* colour coordinates

Figure 3 Experimental apparatus



with corresponding film thicknesses from 40 to 800 nm in steps of 1 nm. Values of the colour coordinates were obtained from a chromatic interferogram of a static contact, and the film thickness values from a monochromatic interferogram of the same contact.

The film thickness resolution is approximately 1 nm, and measurement accuracy is 3 nm. The lateral resolution of the instrument is about 1.2 μm. To confirm the validity of the measurement technique, an experimentally determined static contact shape was compared with one calculated according to Hertzian theory.[9] **Figure 2** shows an experimental surface deformation profile taken across one half of a static contact and its comparison with a calculated Hertzian profile. This figure also shows values obtained by monochromatic interferometry for a wavelength of 633 nm. The excellent correspondence not only between the experimental results, but also between the experimental results and the calculated values can clearly be seen.

Since evaluation is carried out by a computer program, a conventional optical test rig with a microscope and 35 mm camera can be used (**Figure 3**). Chromatic interferograms are

Table 1 Lubricant properties

	NC 500	*SR 600*
Atmospheric viscosity at 23°C, Pa s	0.321	0.240
Pressure–viscosity coefficient at 23°C, GPa^{-1}	31	16
Density at 20°C, 0.1 MPa, kg/m^3	914	890
Refractive index at 23°C, 0.1 MPa	1.5024	1.4902

Table 2 Characteristics of contacting materials

	Glass disc	*Sapphire disc*	*Steel ball*
Modulus of elasticity, GPa	81	465	210
Poisson's ratio	0.208	0.3	0.3

recorded on reverse colour film and digitised. The basic parts of the test rig that was used consist of a ball and a transparent disc. The ball has 25.4 mm diameter and is made of AISI 52100 steel. The transparent disc is made of homogeneous optical crown glass BK7 or monocrystalline sapphire. Its lower surface is coated with a thin chromium layer. The ball is driven by an AC servomotor through a flexible coupling and a drive shaft. The disc is driven by the ball in nominally pure rolling.

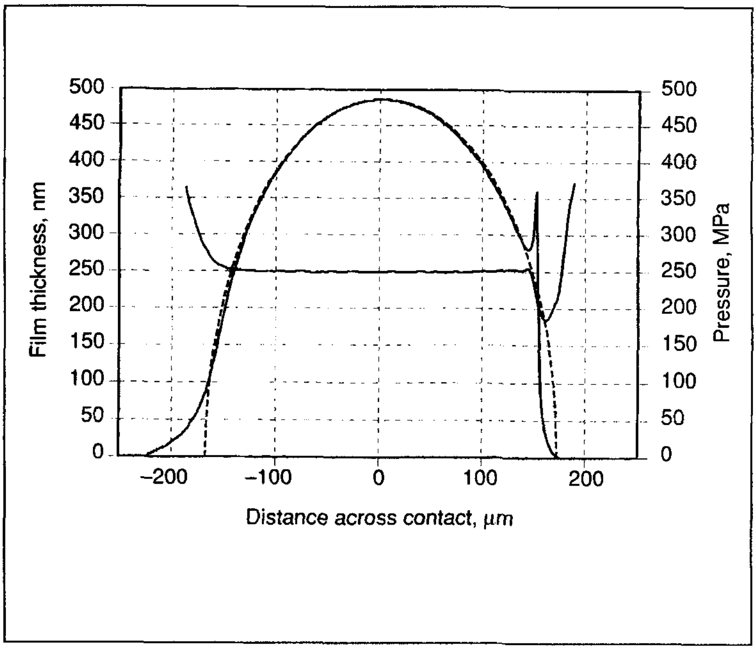
Experimental conditions and material properties

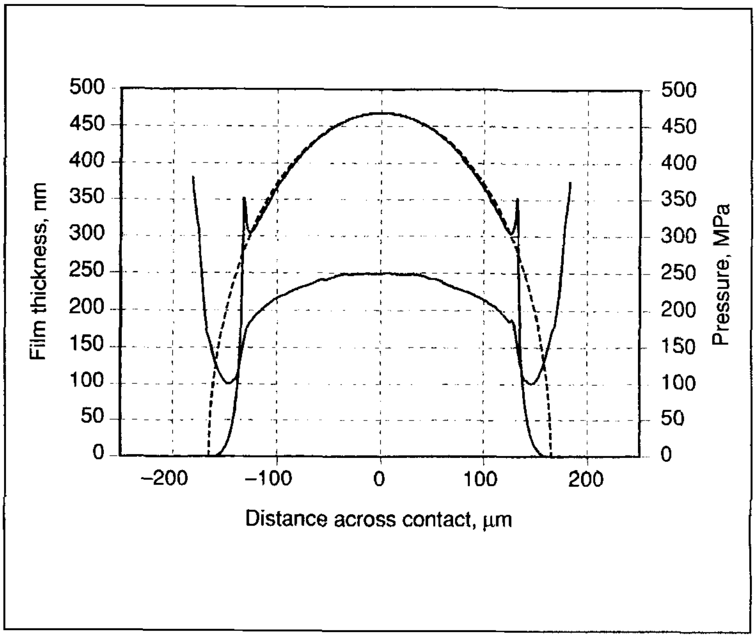
The lubricants chosen for the investigation were a naphthenic base oil, NC 500, and a paraffinic base oil, SR 600, with the properties given in **Table 1**. All tests were carried out under nominally pure rolling at a temperature of 23°C±0.5°C. The characteristics of the contacting materials used in this study are summarised in **Table 2**.

Refractive index correction

It is well known that the refractive index of an EHD lubricant film changes with the contact pressure, which is why film thicknesses evaluated from chromatic interferograms must be corrected. As only central and minimum film thicknesses were used in this study, it was not necessary to use the three-dimensional EHD pressure distribution for this correction. **Figure 4**

Figure 4 Pressure profiles and corresponding EHD film thickness profiles





is a comparison of Hertzian pressure profiles with those obtained from numerical solution[5] and corresponding EHD film thickness profiles both along the centre line in the direction of motion, and across the direction of motion at the location of minimum film thickness. From this, it can be seen that, while Hertzian pressure is very appropriate for central film thickness, the same is not true for minimum film thickness. However, for the operating conditions used in this study, the greatest difference between non-corrected minimum film thickness and that corrected considering EHD pressure, was found to be about 0.8%. This is why the central film thickness was corrected according to Hertzian pressure, and no pressure correction was used for minimum film thickness.

Dimensionless parameters

Two groups of dimensionless parameters are used in this paper – the Moes dimensionless group, and dimensionless parameters used by Hamrock and Dowson. The relation between these two groups is as follows:

- the Moes dimensionless central film thickness parameter

$H_{\mathrm{cen}} = (h_{\mathrm{cen}}/R)(2U)^{-1/2}$

- the Moes dimensionless materials parameter

$L = G(2U)^{1/4}$

- the Moes dimensionless load parameter

$M = W(2U)^{-3/4}$

where the dimensionless speed parameter is $U = u\eta_0/(E'R)$, the dimensionless load parameter is $W = F/(E'R^2)$, and the dimensionless materials parameter is $G = \alpha E'$. In these equations u is the mean surface velocity, η_0 is the viscosity of the lubricant at atmospheric pressure, E' is the reduced modulus of elasticity, R is the reduced radius of curvature, F is the applied load, and α is the pressure–viscosity coefficient of the lubricant.

RESULTS AND DISCUSSION

Figures 5 to **7** show comparisons of measured central and minimum EHD film thicknesses with numerical solutions,[8]

Figure 5 Comparison of central and minimum EHD film thicknesses for a dimensionless materials parameter *G* of 1916

■ $h_{c\text{-exp}}$
● $h_{min\text{-exp}}$
— $h_{c\text{-Hamrock–Dowson}}$
- - - $h_{min\text{-Hamrock–Dowson}}$
▼ $h_{c\text{-num}}$
▲ $h_{min\text{-num}}$

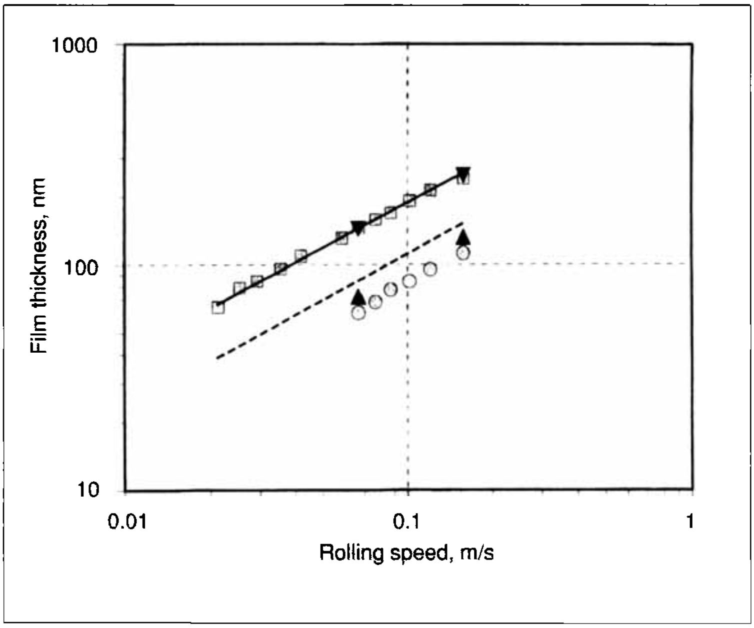


Figure 6 Comparison of central and minimum EHD film thicknesses for a dimensionless materials parameter *G* of 3713

■ $h_{c\text{-exp}}$
● $h_{min\text{-exp}}$
— $h_{c\text{-Hamrock–Dowson}}$
- - - $h_{min\text{-Hamrock–Dowson}}$
▼ $h_{c\text{-num}}$
▲ $h_{min\text{-num}}$

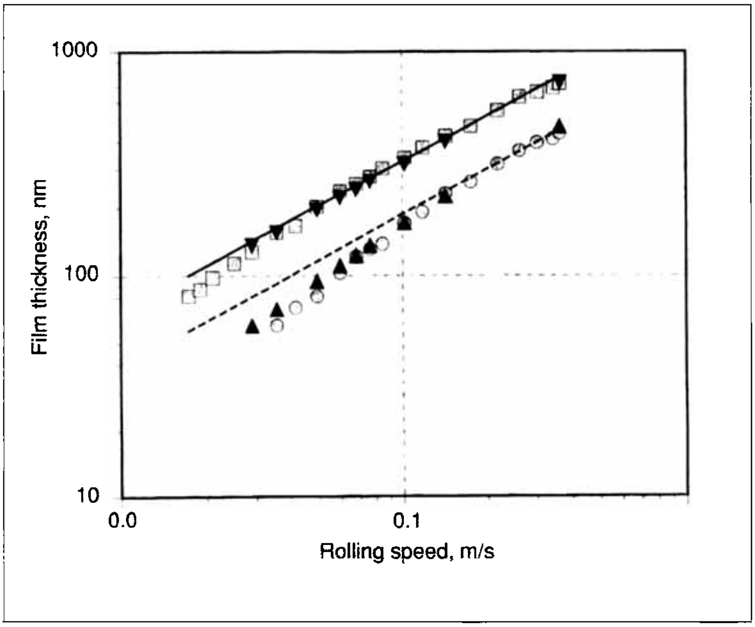
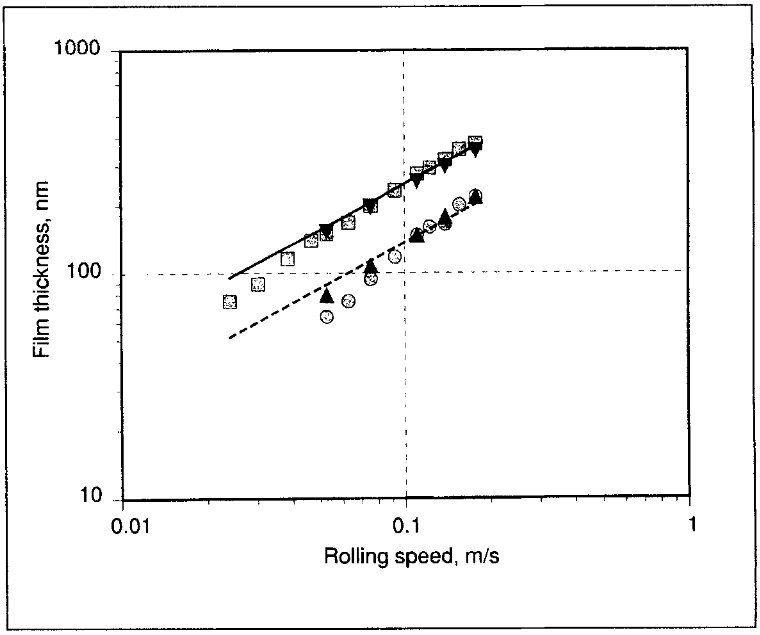


Figure 7 Comparison of central and minimum EHD film thicknesses for a dimensionless materials parameter *G* of 9220



and Hamrock and Dowson film thickness equations, for a dimensionless materials parameter G of 1916, 3713, and 9220, respectively. It can be seen that, with decreasing rolling speed, both the measured minimum film thicknesses and those obtained by numerical solution fall more rapidly than the values predicted by the Hamrock and Dowson equation. There is thus an intersection below which the Hamrock and Dowson equation becomes optimistic, and the position of this intersection depends on the operating conditions. This correlates well with the results obtained by Koy and Winer,[3] who found the measured minimum film thickness to be about 30% greater than the Hamrock and Dowson prediction for a G of 10451 and very thick films. However, with their value of 0.751 for the exponent on the dimensionless speed U, one can also find an intersection with the Hamrock and Dowson equation (at about 40 nm).

Some differences can also be seen in the behaviour of the central film thickness for different values of the dimensionless materials parameter. For a G of 1916, the measured central film thickness follows the Hamrock and Dowson equation perfectly down to 50 nm, in very good agreement with extensive

Figure 8 Dependence of the ratio h_c/h_{min} on load parameter M for materials parameter L = 11 and 14

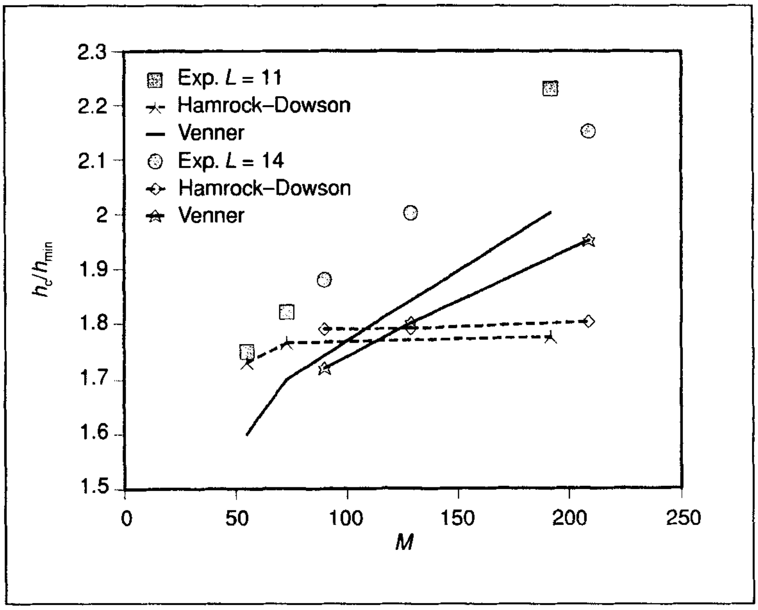
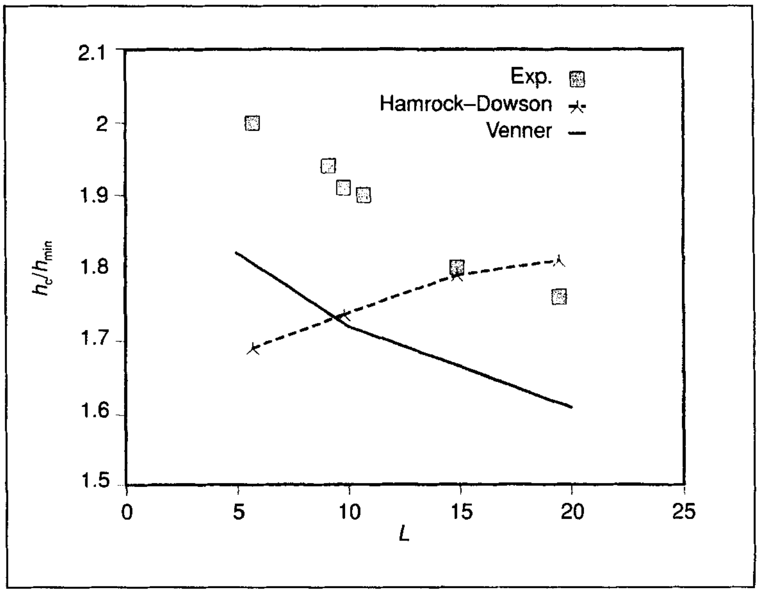


Figure 9 Dependence of the ratio h_c/h_{min} on materials parameter L for load parameter M = 80



experimental work carried out by Johnson *et al.*[10] However, for higher values of the dimensionless materials parameter, the experimental data fell below the theoretical with decreasing rolling speed.

In work done in the late 1980s and early 1990s, the ratio between the central and minimum film thicknesses was found to be not necessarily a constant. Venner[11] calculated the values of this ratio to be between 1.3 and 3.1, depending on the Moes dimensionless materials (L) and load (M) parameters. Similar findings were obtained in the present study, and some additional comparisons are therefore given. **Figures 8** and **9** show comparisons between the results obtained from measurements, from Venner's calculations, and from the Hamrock and Dowson equations. **Figure 8** shows the dependence of the ratio between central and minimum film thicknesses on load parameter M for two values of materials parameter L ($L = 11, 14$). In **Figure 9**, load parameter M is held constant ($M = 80$) and the central-to-minimum film thickness ratio is plotted as a function of materials parameter L. From these comparisons, there is evidently good agreement between the experimental and the Venner data. It can be seen that minimum film thickness is more strongly dependent on load than the Hamrock and Dowson equations predict. Similar results were obtained by Smeeth and Spikes for very high loads.[7] The same correlation between the experimental and the Venner data can be found regarding the influence of materials parameter L on the central-to-minimum film thickness ratio, where the Hamrock and Dowson equations predict quite different behaviour.

More recently, we have used a new measurement system[12] for the study of very thin lubricant films to support the above-mentioned results, and excellent agreement with the Venner numerical solution down to a few nanometres has been found.[13]

CONCLUSION

Accurate central and minimum EHD film thickness values were obtained for a wide range of operating conditions. The experimental results correlated very well with the Venner numerical calculations. The ratio between the central and minimum film thicknesses was confirmed to have a stronger dependence on materials and load dimensionless parameters than the Hamrock and Dowson equations predict. For higher materials parameters, some deviation from the Hamrock and Dowson central film thickness equation was observed with decreasing rolling speed.

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