Monica Ratoi-Salagean[1] and Hugh A. Spikes[1]

THE LUBRICANT FILM-FORMING PROPERTIES OF MODERN FIRE RESISTANT HYDRAULIC FLUIDS

REFERENCE: Ratoi-Salagean, M. and Spikes, H.A. "The Lubricant Film-Forming Properties of Modern Fire Resistant Hydraulic Fluids", Tribology of Hydraulic Pump Testing, ASTM STP ****, A. B. Name, Ed. American Society for Testing and Materials, Philadelphia, 1996.

ABSTRACT: Fire resistant hydraulic fluids tend to show significantly poorer tribological performance in hydraulic systems than conventional mineral oil-based fluids. There have recently been performance problems associated with increases of operating temperatures of mining hydraulics. This paper describes measurements of the elastohydrodynamic and boundary film-forming properties of a range of different hydraulic fluid types at temperatures up to 80°C. These are compared with friction and wear results obtained using the same fluids.

KEYWORDS: elastohydrodynamic lubrication, film thickness, hydraulic fluid, fire resistant, wear

INTRODUCTION

Fire resistant hydraulic fluids are widely used in mining and other safety-critical applications where there is a significant risk from fire. Many of these fluids contain a high proportion of water which confers their resistance to ignition, although others are based upon synthetic materials which are either less volatile or possess intrinsically more resistance to combustion than mineral oils.

One limitation of water-based hydraulic fluids and also of some synthetics is that their lubricating properties tend to be significantly poorer than conventional, mineral oil-based fluids. In some cases this is because they form thinner hydrodynamic films that mineral oils of equivalent viscosity. This is particularly the case with some water-based fluids. Some

---

[1] Research student and Reader, respectively, Tribology Section, Department of Mechanical Engineering, Imperial College, London SW7 2BX, England

fire resistant hydraulic fluids may also possess less effective boundary lubricating properties than mineral oil blends. Because hydraulic pumps generally rely for their lubrication on the fluid being pumped, the inferior lubrication properties of many fire resistant fluids mean that pumps have to be de-rated and also often give performance problems such as high wear or low fatigue life in service.

A recent trend which has exacerbated this problem in mining applications in the United Kingdom is a significant increase in the temperature at which hydraulic fluids are operating. Whereas maximum hydraulic fluids temperatures used to be about 60 to 70°C, temperatures as high as 80°C are now common. This results from higher ambient temperatures, either because of deeper seams or from the large quantities of energy-dissipating, electrical equipment required for increased mine mechanisation. This rise in temperature is believed to have contributed to an increase in pump failure rates in the last two years. One particular problem has been the failure of gear pumps with needle roller bearings. Failures have taken place within "days or weeks" and have been concentrated in mine areas where ambient temperatures are high, at about 38°C.

A useful, fundamental measure of the lubricating ability of fluids is the film thickness that they form in concentrated contacts. This indicates the extent to which they are likely to form separated films and thus limit wear in high pressure contacts such as are present in gear pumps. This paper describes measurements of the film-forming properties of a range of different commercial fire resistant hydraulic fluids in concentrated contacts at temperatures up to 80°C, with a special emphasis on water-based fluids. The friction and wear performance of some of the fluids have also been determined over the same temperature range. The main aim was to compare the behavior of different types of fluids at the high temperatures now being reached in some mining applications and thus to indicate appropriate fluids for such applications.

BACKGROUND

According to ISO standard 6743/4 there are four main categories of fire resistant fluid, HFA to HFD, as indicated in table 1 (1). This specification is not normally considered to include some aviation hydraulic fluids based on synthetic hydrocarbons which possess moderate fire resistance (2), although the family HDFU may encompass these as well as silicone-based fluids and recently developed water-free glycol-based materials.

Most of these fluids, and in particular the water-based types, are poorer lubricants than conventional mineral oil-based hydraulic fluids, whose evolution has been charted by Grover and Perez (3). Of the fire resistant fluids, HFD phosphate ester fluids are generally considered to have the best lubricating characteristics, followed by the HFB class. HFAE oil in water emulsions are usually regarded as the poorest lubricants whilst HFAS and HFC fluids are intermediate (4).

This order of effectiveness tends to be reflected in their applications. Thus HFB fluids are employed, together with some HFCs or even mineral oils, in demanding applications such as mobile and static hydrostatic power transmissions whilst HFAE fluids are confined to low contact pressure, static or slow moving applications such as longwall powered roof supports (5).

TABLE 1--Classes of fire resistant fluid

Class	Sub-class	Compositional requirements	Typical composition
HFA	HFAE	Oil in water emulsions, less than 20% wt. combustible materials	Typically 5% wt. oil
" "	HFAS	Solutions of chemical in water, less than 20% combustible materials	Typically 1 to 5% wt. hydrocarbon phase as micro-emulsion or solution
HFB		Fire resistant water in oil emulsions	Typically 40% wt. water
HFC		Fire resistant polymer solutions, at least 35% wt. water	Typically 15% high MWt polyglycol, 40% monoglycol, 45% water
HFD	HFDR	Fire resistant synthetic fluids based on phosphoric acid esters	Typically trialkyl and/or triaryl phosphate
" "	HFDS	Fire resistant synthetic fluids based on chlorinated hydrocarbons	
" "	HFDU	Fire resistant synthetic fluids of other types	e.g. silicate esters

The performance problems associated with water-based fluids have been discussed by a number of authors and include low fatigue life, high wear rate and cavitation erosion (5)-(8). There appear to be three main reasons for the inferior lubricating performance of fire resistant fluids as compared to mineral oils;

(i) poor hydrodynamic or elastohydrodynamic film formation, related either to the low viscosity and pressure viscosity coefficient of water or to the low pressure viscosity coefficient or shear thinning behavior of some synthetics

(ii) poor boundary lubrication associated either with the difficulty of finding boundary additives effective in water systems or the lack of suitable additives soluble in some synthetics

(iii) corrosion, erosion or embrittlement caused by the presence of water

One particular problem associated with the use of water-based fluids is their relatively poor film-forming properties in high pressure, elastohydrodynamic-type contacts. Low film thickness results in high levels of solid/solid contact which has been shown to lead to high wear (9), reduced fatigue (10) and increased likelihood of seizure (11). Water itself has very little elastohydrodynamic film-forming ability due to its very low pressure-viscosity coefficient and this is partially reflected in the film-forming properties of most water-based fluids.

The film-forming properties of water in oil emulsions have been studied using optical interferometry by Hamaguchi (12) and later by Wan (13). These authors showed that for most emulsions, the EHD film thickness formed is that predicted from the emulsion base oil. In practice this is a good deal less than that predicted from the emulsion itself which is generally more viscous than the component base oil. Wan noted, however, that W/O emulsion having very small water droplet size tend to form slightly thicker films than predicted from the viscosity of the component oil (13).

Wan also examined the EHD film-forming properties of HFC-type polyglycol solutions (14). He showed that the presence of even modest proportions of water in monoglycol and polyglycol greatly reduces the pressure viscosity coefficient of the blend, leading to poor film formation.

O/W

The film-forming properties of water in oil emulsions have been extensively investigated (15)(16)(17). The key to the performance of this type of fluid appears to be the ability of the oil phase to wet the rubbing surfaces and thus form a localised pool of oil in the rubbing contact inlet. At low sliding speeds, many oil in water emulsions are able to do this and thus form lubricant films close to those produced by the water-free oil component. However at some critical speed, which depends strongly upon the emulsifier type and concentration, the supply of oil due to wetting cannot keep up with the contact requirements a severe starvation and film collapse occurs (18). It has recently been shown how the composition of O/W emulsions can be optimised to maximise surface wetting properties and thus film formation at high speeds (19).

Very little work has been carried out on the film-forming properties of HFAS-type fluids although their stability and rheological properties have been outlined by Rasp (20).

All the above work was carried out at relatively low temperatures, between room temperature and about 50°C, and it would be of considerable interest to determine and compare the film-forming properties of fire resistant hydraulic fluids at higher temperature, for reasons outlined in the introduction to this paper. One cause of the lack of previous high temperature measurements is that it was not possible until recently to measure film thicknesses in contact below about 50 nm. In practice, at temperatures above 50°C, because of the reduced viscosity of the fluids, film thickness can fall considerably below this limit. In the last few years, however, a new technique has been developed which is able to measure film formation in rolling contact down to less than 2 nm (21). This means that it is not only possible to measure the film-forming properties of fire resistant fluids at high temperatures but also to examine some of their boundary film forming properties.

The aim of the work described in this paper was to make such film thickness measurements on a range of fire resistant hydraulic fluids in the high temperature range in order to compare their performance under these conditions.

EXPERIMENTAL TECHNIQUES

Elastohydrodynamic/Boundary Film Thickness Measurement

Elastohydrodynamic (EHD) film thickness was measured in a rolling concentrated contact using ultrathin film interferometry (21). The principle of the technique is shown in figure 1. A high pressure contact is formed between the flat surface of a glass disc and a reflective steel ball. The glass disc is coated with a thin, semi-reflective layer of chromium on top of which is a layer of silica, about 500 nm thick. White light is shone into the contact and some is reflected from the chromium layer whilst some passes through the spacer layer and any lubricant film present to be reflected from the steel ball. The two beams recombine and interfere and the spacer layer ensures that interference will occur even if no oil film is present.

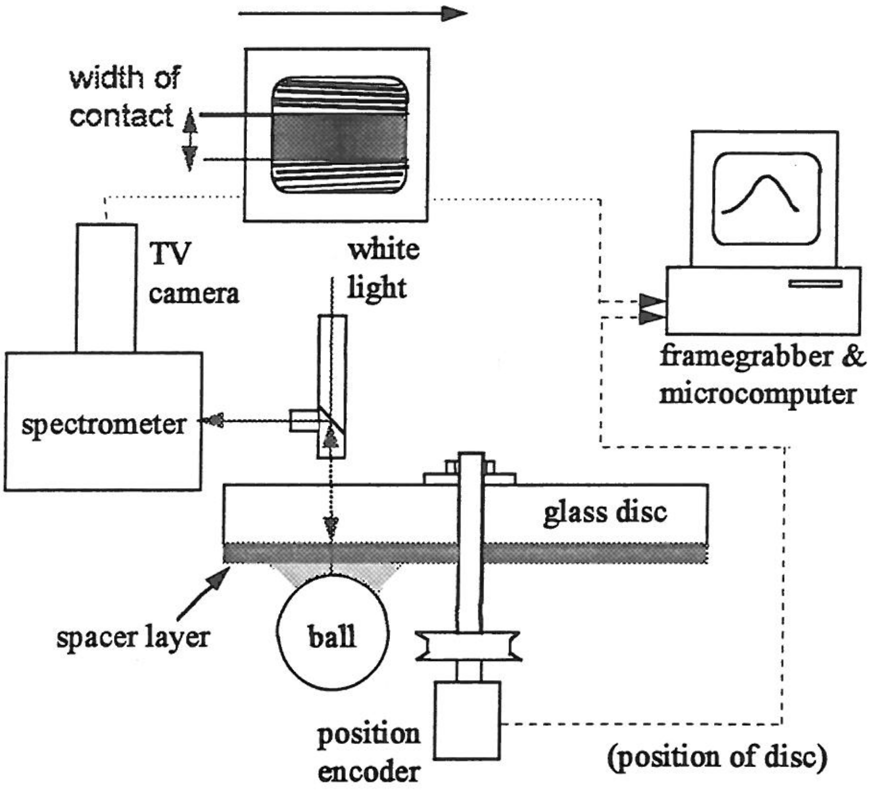

FIGURE 1--Schematic diagram of ultrathin film method

The interfered light from a strip across the contact is then passed into a spectrometer where it is dispersed and detected by a solid state black and white TV camera. A frame grabber is used to capture this image at a pre-selected moment and a microcomputer program determines the wavelength of maximum constructive interference in the central region of the contact. The lubricant film thickness is then calculated from the difference between the measured film thickness and the thickness of the silica spacer layer at that position.

In the test rig, the ball is loaded upwards against the underside of the glass disc and both ball and disc are held within a temperature-controlled, stainless steel chamber. A slotted perspex cover with a side rim is sealed against the top of the glass disc so that the fluid level can be higher than the glass disc to produce a fully-immersed contact. This is important when using some water-based fluids so as to avoid water evaporation from the otherwise very thin out-of-contact track on the glass disc.

In each test, the silica spacer layer film thickness is initially recorded using a position encoder, at a series of set positions around the disc using a dry contact. Fluid is then circulated and a series of film thickness measurements are made at different rolling speeds. In doing this, the position encoder is used to ensure that interference images are detected and grabbed from these same positions where the spacer layer thickness has already been determined.

In the work described in this study the disc was rotated and itself drove the ball in nominally pure rolling. A fresh 19 mm diameter, steel ball of rms surface roughness 11 nm was used for each test. The load applied was 20 N which corresponds to a maximum contact pressure of 0.52 GPa.

Wear and Friction Test Method

To compare friction and wear properties of the test fluids, a high frequency reciprocating rig (HFRR) was used. This is shown in figure 2. A steel ball is loaded and reciprocated against a steel flat. The contact is fully immersed in lubricant whose temperature is controlled to 0.5°C. Friction coefficient is monitored continuously and the average diameter of the wear scar is measured at the end of a test.

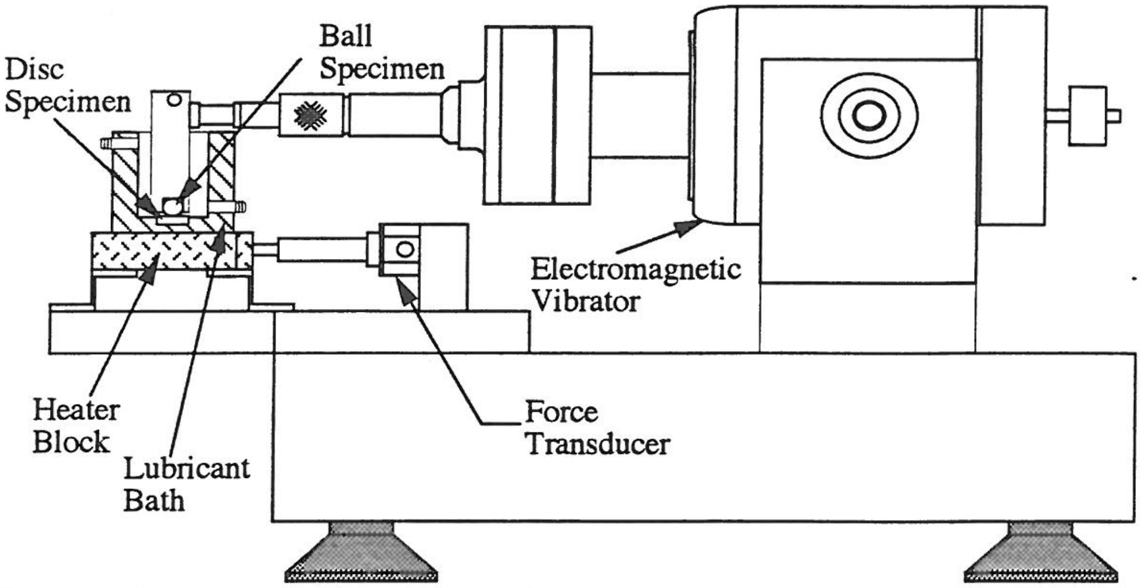

FIGURE 2--HFRR friction and wear tester

This test was designed to compare the wear properties of diesel fuels and is thus suited to studying low lubricity fluids. In the context of the current work it had two other advantages. Firstly, because the motion is reciprocating, the test will operate for a significant proportion of time in the mixed lubrication regime. Thus it is likely to be more responsive to lubricant film-forming ability than a test operating primarily in the boundary regime. Secondly, because of the relatively mild load/speed conditions, there is very little flash temperature heating in the contact, so the test should not be dominated by antiwear or ep additive effects as other, more severe tests might be (22). The HFRR test conditions used in this study are summarised in table 2.

TABLE 2--HFRR test conditions used in this study

Stroke length	1000 μm
Stroke frequency	20 Hz
Load	400 g
Temperature	40°C or 80°C
Test duration	60 minutes
Ball properties	AISI 52100
Disc properties	AISI 52100

FLUIDS TESTED

The fluids tested are listed in table 3. All were fully-formulated, commercial hydraulic products, spanning a range of different classes of fluids obtained from three different suppliers.

TABLE 3--Hydraulic Fluids Tested

Designation	Viscosity Grade	Composition
HM-46	46	Mineral oil based, fully-formulated
HM-68	68	Mineral oil based, fully-formulated
HM-100	100	Mineral oil based, fully-formulated
HFA-1		5% O/W emulsion
HFA-2		5% O/W micro-emulsion
HFA-3		5% O/W micro-emulsion
HFA-4		5% O/W emulsion (high biodegradability)
HFB-68	68	W/O emulsion
HFB-100	100	W/O emulsion
HFC-1	46	Polyglycol/glycol/water type
HFC-2	46	Polyglycol/glycol/water type
HFC-3	46	Polyglycol/glycol/water type
HFD-46	46	Phosphate ester
HFD-68	68	Phosphate ester

Three were mineral oil-based hydraulic fluids having different viscosities and two were phosphate ester-based synthetics. Four were O/W HFA fluids, three were invert HFB fluids and three were glycol-based HFCs

FILM THICKNESS RESULTS AND INTERPRETATION

Mineral Oil-Based Fluids

Figure 3 shows film thickness results for the three mineral oil-based fluids. These, and all other film thickness results in this paper, are shown as log(film thickness) versus log(speed). According to EHD theory, the central film thickness, h_c is given by (23);

$$h_c = k(U\eta_o)^{0.67}(\alpha)^{0.53} \qquad (1)$$

where U is the mean rolling speed, η_o is the viscosity, and α is the pressure viscosity coefficient of the lubricant. Thus so long as it obeys EHD theory, a given fluid should give a straight line of gradient approximately 0.67 on a log(h_c) versus log(U) plot. Any deviation from such behavior is indicative of non-classical EHD behavior such as starvation, non-Newtonian fluid behavior or the presence of boundary films.

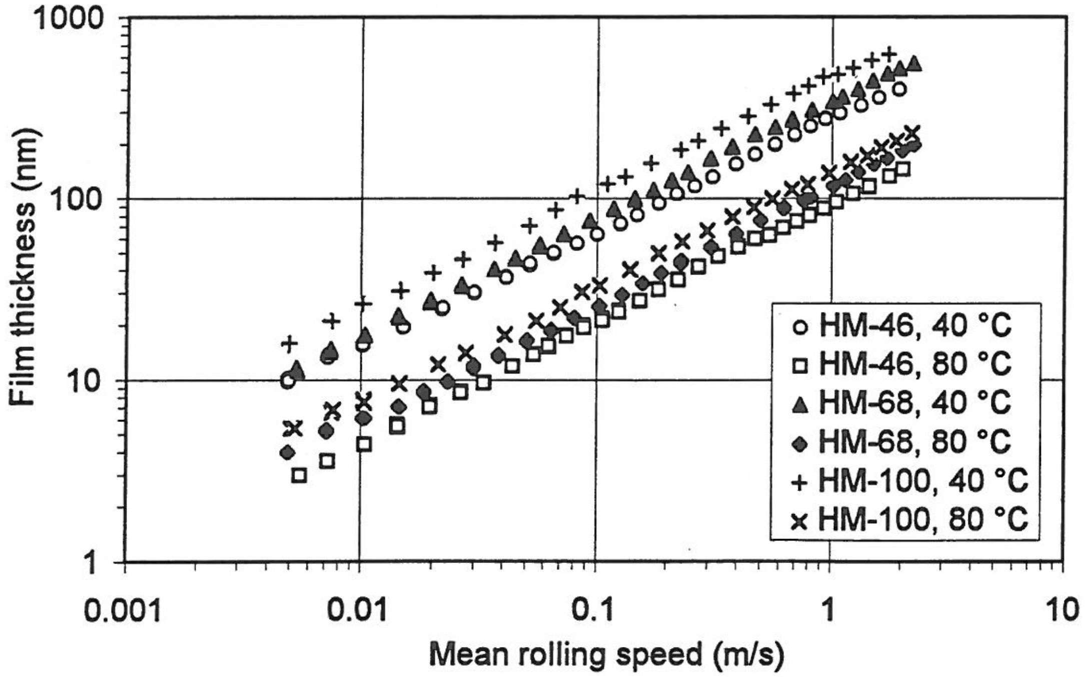

FIGURE 3--Film formation by mineral oil-based hydraulic fluids

All of these mineral oil-based fluids give straight line plots at both temperatures, indicative of conventional EHD behavior down to 3 nm. The film thicknesses at 80°C are lower than at 40°C primarily because the viscosities, η_o of the fluids are reduced at the higher temperature and also, to a small extent because the pressure viscosity coefficients, α are reduced.

These mineral oil results will be used as reference values with which to compare the other types of hydraulic fluid.

Type HFD Fluids

Figure 4 shows the film-forming behavior of the two HFD fluids. These also obey EHD theory over most of the speed/film thickness range although there is a slight deviation at very thin films at 80°C. The plots appear to flatten at film thicknesses below 20 nm, which may indicate a surface film of enhanced viscosity (24).

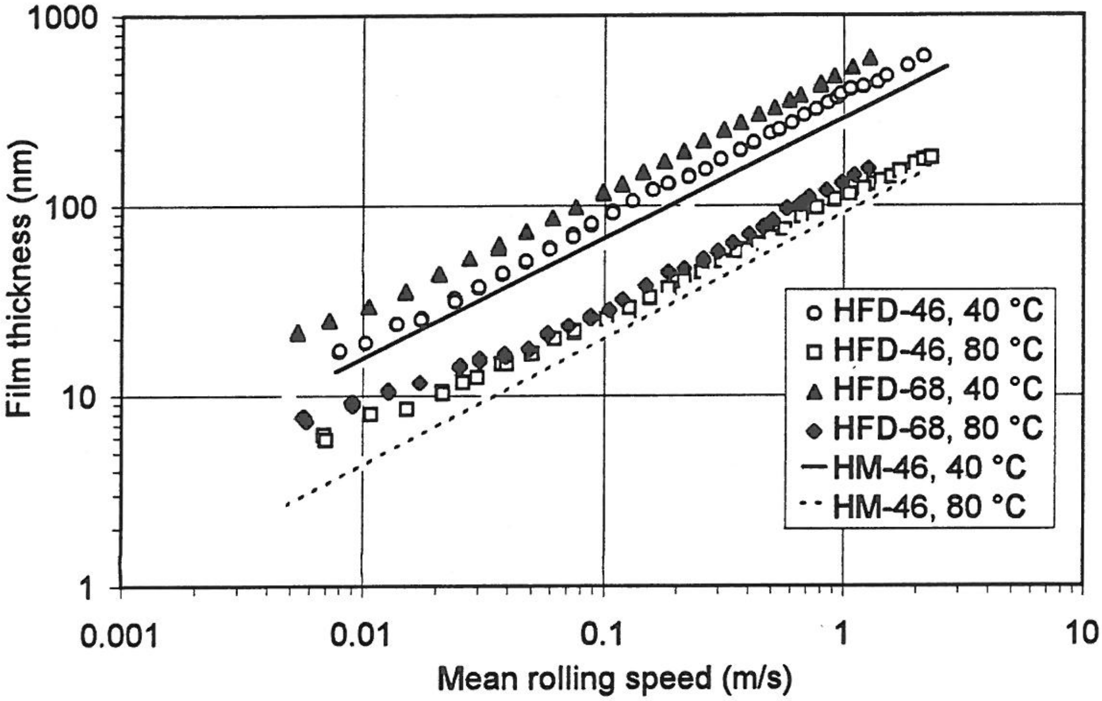

FIGURE 4-- Film formation by HFD hydraulic fluids
(mineral oil shown as solid/dashed lines)

In figure 4, the performance of the mineral oil-based fluid HM-46 is also shown as solid/dashed lines. The corresponding phosphate ester gives a significantly thicker film than the mineral oil at 40°C. This is probably because the phosphate ester has a larger pressure viscosity coefficient than the mineral oil. The difference at 80°C is less striking than at 40°C. The same trend is present with the other HFD fluid. Phosphate esters generally have quite low viscosity indices (VI) and thus thin more rapidly with temperature than mineral oils. At 80°C this will tend to nullify the effect of the higher pressure viscosity coefficient of the phosphate esters compared to the mineral oils.

Type HFB Fluids

Figure 5 shows results for the two HFB invert emulsions. Both fluids give reasonably linear plots except at very high or at slow speed. Interestingly, both fluids form similar film thicknesses at 40°C and the HFB-68 is the thicker of the two at 80°C, even though the HFB-100 has higher bulk viscosity. Previous work on model W/O emulsions has suggested that EHD film thickness depends upon the viscosity of the base fluid rather than on the generally higher viscosity of the bulk emulsion (12). The current results thus imply that the two fluids contain similar viscosity base oils. It should be noted that in low pressure, hydrodynamic contacts the benefits of the more viscous fluid might be more evident.

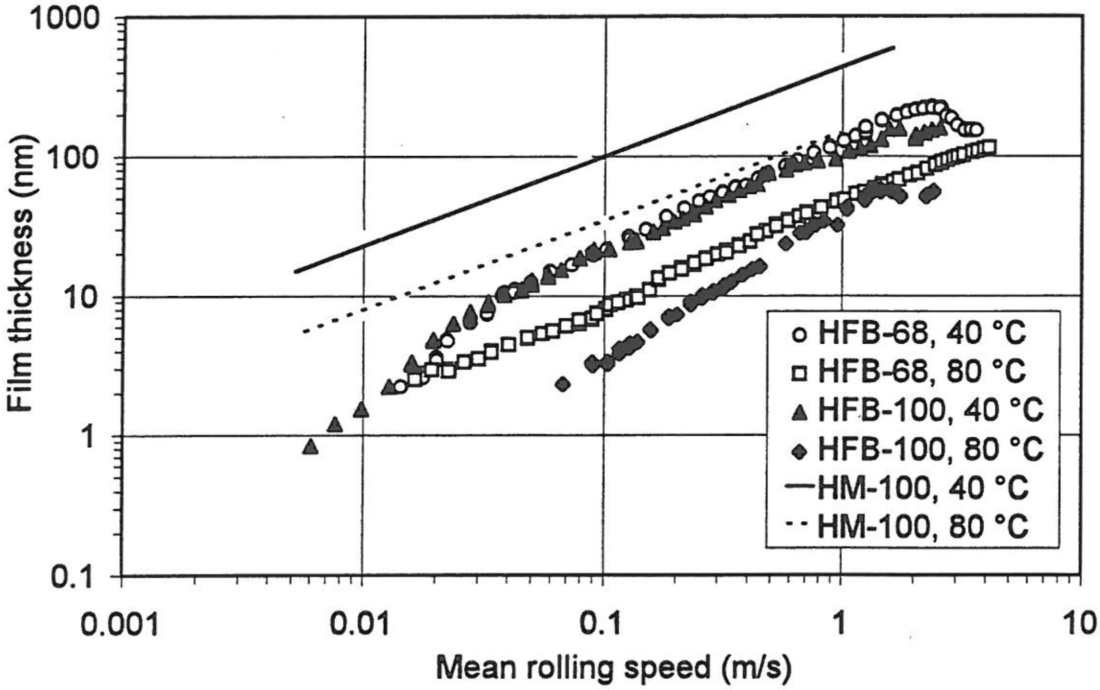

FIGURE 5--Film formation by HFB hydraulic fluids
(mineral oil shown as solid/dashed lines)

Figure 5 also includes the mineral oil-based HM-100 film thicknesses as solid/dashed lines. It can be seen that HFB-100 fluid gives a much lower film thickness than the corresponding mineral oil

The origin of the fall in film thickness at high speed with HFB-68 at 40°C is not known. It may be produced by some starvation in the inlet. One interesting feature is that both fluids show a steepening of the film thickness/speed plot at 40°C; to yield thinner than expected films in this region. This type of behavior has been noted previously when a mixed base fluid consisting of a low viscosity polar ester and a higher viscosity non polar hydrocarbon was tested (25). The more polar component concentrated near the polar solid surfaces to produce a low viscosity surface film.

Type HFC Fluids

The three HFC fluids tested are plotted separately in figure 6. All three show an increase of film thickness with speed, with gradient very approximately 0.67. However within this general trend, two of the fluids show quite complex behavior. Fluid HFC-1 shows a marked plateauing at a film thickness of about 25 nm. Fluid HFC-2 forms an irregular boundary film of about 5 nm thickness and also exhibits a pronounced plateauing and even a small, temporary fall in film thickness at about 25 to 20 nm. Fluid HFC-3 showed far more regular behavior and gives thicker films.

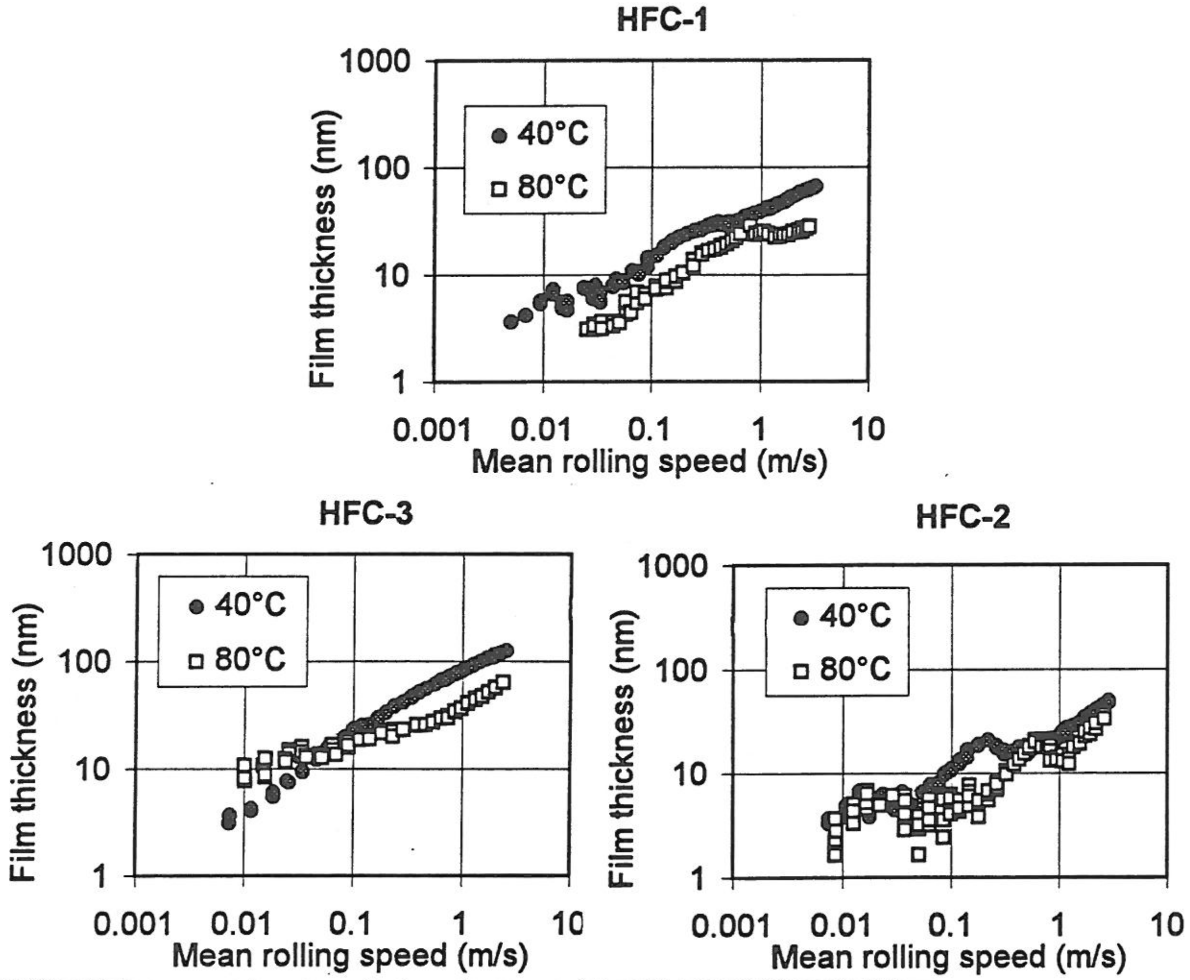

FIGURE 6--Film formation by HFC hydraulic fluids

This type of intermediate levelling-out of film thickness with speed at about 10 to 30 nm has also been observed with solutions of polar VI improver polymers in mineral oils, where it was ascribed to the presence on the solid surfaces of a layer of polymer solution about one random coil diameter in thickness (i.e. about 20 nm) which had enhanced polymer concentration and thus viscosity (26). Since HFC fluids contain some high molecular weight polyglycol polymer this may also be the origin of the observed behavior with these two fluids. Alternatively it may reflect some other form of fluid structuring close to the rolling solid surfaces. Polyglycol/monoglycol/water mixtures are known to form quite complex internal fluid structures (14). These structures and consequently their viscosities and pressure viscosity coefficients are likely to be modified in the vicinity of solid surfaces.

All of the HFC fluids give much thinner EHD films than their mineral oil counterparts.

Type HFA Fluids

Figure 7 shows results for the four HFA fluids at 40°C. Note that the film thickness scale on this figure is different from the preceding ones. At 80°C the films formed were so thin that the rubbing surfaces were damaged during tests so it was not possible to acquire reliable results. All four give similar behavior, with a boundary film at low speeds which was 1.5 to 5 nm thick depending upon the emulsion. This film thickness was broadly independent of speed although the film collapsed to zero when motion was halted. Similar behavior has been seen previously for boundary additives in hydrocarbon-based oils (27).

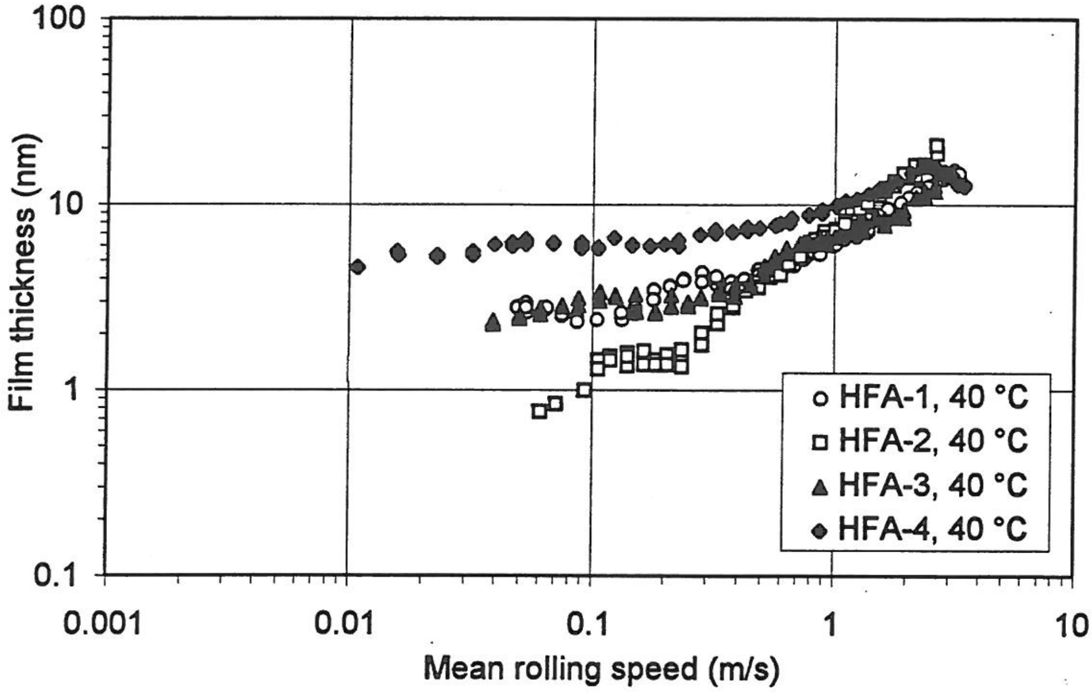

FIGURE 7--Film formation by HFA hydraulic fluids at 40°C

At higher speed, elastohydrodynamic films start to form for all fluids but these do not reach more than 20 nm thickness within the speed range studied.

This film thickness behavior is quite poor. Previous studies using O/W emulsions for application as rolling oils have tended to show much thicker elastohydrodynamic film formation in the slow speed range. Figure 8 shows the results for a commercial rolling oil emulsion where it can be seen that the film thickness first rises with a gradient of about 0.67, then collapses and then starts to rise once more. As outlined in the background section of this paper, the slow speed EHD film formation is due to the build up of a reservoir of oil in the contact inlet caused by wetting. The film collapse at higher speed then occurs when this reservoir cannot be replenished fast enough. For the emulsions tested in the current study there appears to be negligible slow speed EHD film formation. This may be because the emulsions have been formulated in such a way that the oil droplets are unable to wet the solid surfaces.

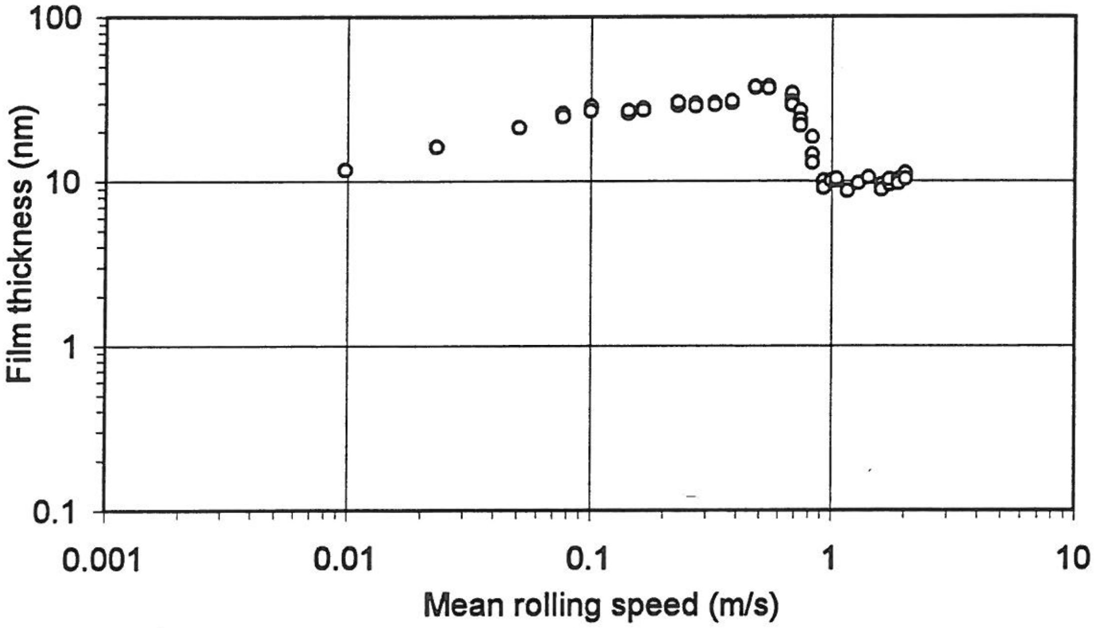

FIGURE 8--Film formation by a commercial O/W rolling emulsion

WEAR RESULTS

Friction coefficient and wear test results are listed in table 4 overleaf. For most of the fluids tested, the wear was less at 80°C than at 40°C, suggesting that antiwear additives or other surface chemical behaviour was being activated at the higher temperature. The exception was HFC-3 which showed very poor wear performance at 80°C.

Table 4 also lists the measured film thickness at 0.1 m/s rolling speed. There was quite good correlation between the wear scar diameters and the film thicknesses at 40°C, as shown in figure 9. The correlation at 80°C was poor, presumably because of additive effects.

TABLE 4--Wear scar and friction coefficient results

Fluid	Temperature, °C	Wear scar diameter, µm	Friction coefficient	Film thickness at 0.1 m/s, nm
HM-68	40	109	0.141	80
	80	106	0.148	23
HFA-1	40	218	0.146	2.5
HFA-2	80	228	0.164	1.5
HFB-68	40	161	0.128	20
	80	111	0.129	7
HFC-1	40	192	0.132	11
	80	193	0.117	7
HFC-3	40	173	0.099	20
	80	260	0.133	18
HFD-68	40	97	0.121	110
	80	93	0.126	30

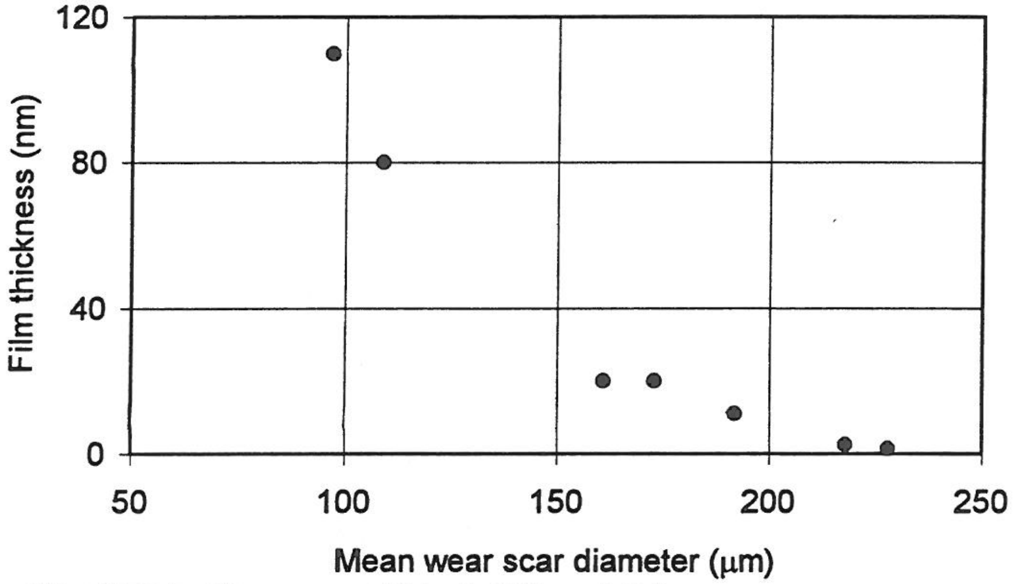

FIGURE 9--Correlation between wear and film thickness measurements at 40°C

DISCUSSION

The results show a wide diversity of behavior from conventional EHD performance for mineral oils and phosphate esters to a combination of boundary film formation with only a very thin EHD film for type HFA emulsions.

The film thickness results are broadly in agreement with known pump performance; i.e. mineral oil/phosphate esters are the best lubricants, W/O emulsions somewhat less effective, polyglycols/glycols much less effective and O/W emulsions the worst. The wear results correlate quite well with the film thickness measurements at 40°C but not at 80°C, possibly because additive effects control wear at the higher temperature. This raises the question of whether wear or film thickness measurements are more relevant in determining real pump performance at high temperatures. The authors suspect that film thickness may be more relevant under the complex combination of conditions found in pumps. The fact that failures tend to occur at higher temperatures whilst the measured wear performance is much the same at both temperatures may support this.

There were quite striking differences in behaviour between the various HFC fluids and some fluids showed very interesting non-linear film-forming behavior. Clearly further work needs to be carried out on these fluids. It also appears that there may be scope for improving the lubricating properties of some HFA hydraulic fluids

CONCLUSIONS

(i) The EHD and boundary film-forming properties of a range of commercial hydraulic fluids has been measured. Some wear properties have also been determined.
(ii) There are large differences in the thickness of films formed by different classes of fluid, spanning two orders of magnitude from mineral oil-based fluids to HFA O/W emulsions.
(iii) The relative film formation correlates with known relative performance in lubricating hydraulic pumps.

ACKNOWLEDGEMENTS

The authors wish to thank Dr David Yardley of E.D. Yardley Associates for much valuable advice and discussion and also those companies who kindly provided hydraulic fluids for testing.

REFERENCES

1. ISO standard 6743/4
2. Snyder, C.E. and Geschwender, L.J. "Fire Resistant Hydraulic Fluids", STLE, Presented at STLE Annual Meeting, Chicago, May 1995, preprint 95-AM-4D-1, to be published in Tribology Transactions.
3. Grover, K.B. and Perez, R.J. "The Evolution of Petroleum Based Hydraulic Fluids", Lubrication Engineering 46, pp. 15-20, (1990).
4. Spikes, H.A. "Wear and Fatigue Problems in Connection with Water-Based Hydraulic Fluids." J. Synthetic Lubrication 4, pp. 115-135, (1987).

5. Myers, M.B. and Townsend, F. "Fire-resistant Fluid and Lubricant Trends Within the Mining Industry", Proc. Intern. Conf., *Tribology in Metal Extraction*, Sept. 1994, Instn. .Mech.Engnrs. C336/84, pp. 95-104,
6. Wymer, D.G. "The Use of Water Hydraulics in Machines in Mechanised Gold Mining in South Africa", Proc. Intern. Conf. *Mining and Machinery*, Brisbane, July 1979, pp. 320-328.
7. Rudston, S.G. and Whitby, R.D. "Recent Developments in the Performance Properties of Water Based Cutting and Hydraulic Fluids", J. Synthetic Lubrication 2, pp. 183-212, (1985).
8. Rubery, A.M. "Compatibility of Performance and Fluid Properties", Inst. Petr. Intern. Symp. *Performance Testing of Hydraulic Fluids*, Oct. 1978, London, ed. R Tourret and E.P. Wright, publ. Heyden and Son Ltd., London.
9. Sastry, V.R., Sethuramiah, A. and Singh, B.V. "A Study of Wear Under Partial EHD Conditions", Proc. 11th Leeds-Lyon Symposium on Tribology, Leeds, 1984, Mixed Lubrication and Lubricated Wear, Ed. D Dowson et al. Publ. Butterworths, 1985.
10. *Life Adjustment Factors for Ball and Roller Bearings*, An Engineering Guide Sponsored by the Rolling-Elements Committee, The Lubrication Division of ASME, 1971.
11. Dyson, A. "The Failure of Elastohydrodynamic Lubrication of Circumferentially Ground Discs", Proc. Inst. Mech. Engnrs. 190, (1976), pp. 52-76.
12. Hamaguchi, H., Spikes, H.A. and Cameron, A. "Elastohydrodynamic Properties of Water in Oil Emulsions." Wear 43, pp. 17-24, (1977).
13. Wan, G.T.Y., Kenny, P. and Spikes, H.A. "Elastohydrodynamic Properties of Water Based Fire-Resistant Hydraulic Fluids." Tribology International 17, pp. 309-315, (1984).
14. Wan, G.T.Y and Spikes, H.A. "The Elastohydrodynamic Lubricating Properties of Water-Polyglycol Fire Resistant Fluids." ASLE Transactions 27, pp. 366-372, (1984).
15. Kimura, Y. and Okada, K. "Lubricating Properties of Oil in Water Emulsions." Tribology Transactions 32, pp. 524-532 (1989).
16. Nakahara, T. M., Makino, T. and Kyogoku, K. "Observations of Liquid Droplet Behavior and Oil Film Formation in O/W Type Emulsion Lubrication" Trans ASME J. of Tribology 110, pp. 348-353 (1988).
17. Zhu, D., Bireshaw, G., Clark, S.J. and Kasun, T.J. "Elastohydrodynamic Lubrication with O/W Emulsions", ASME Preprint 93-Trib-4, (1993).
18. Barker, D.C., Johnston, G.J., Spikes, H.A. and Bünemann T. "EHD Film Formation and Starvation of Oil in Water Emulsions." Tribology Transactions 36, pp. 565-572, (1993).
19. Ratoi Salagean, M., Spikes, H.A. and Rieffe, H.L. " Optimising Film Formation by Oil in Water Emulsions" to be presented at STLE Annual Meeting,. Cincinnati, May 1996.
20. Rasp, C.R. "Water Based Hydraulic Fluids Containing Synthetic Components", J. Synthetic Lubrication, 6, pp. 233-251, (1989),.
21. Johnston, G.J., Wayte, R. and Spikes, H.A. "The Measurement and Study of Very Thin Lubricant Films in Concentrated Contacts." Tribology Transactions 34, pp. 187-194, (1991).

22. Spikes, H.A., Bovington, C., Caprotti, R., Meyer, K. and Kreiger, K. "Development of a Laboratory Test to Predict Lubricity Properties of Diesel Fuels and its Application to the Development of Highly Refined Diesel Fuels." Proc. 9th. Int. Colloquium, Technical Academy, Esslingen, Ecological and Economic Aspects of Tribology, Vol. 1, C-11, Jan. 1994.
23. *Ball Bearing Lubrication: the Elastohydrodynamics of Elliptical Contacts*, B T Hamrock and D Dowson, publ. J Wiley, New York, 1981.
24. Guangteng, G. and Spikes, H.A. "Boundary Film Formation by Lubricant Base Fluids". Accepted for publication, Tribology Transactions, May 1995.
25. Spikes, H.A. "Boundary Lubricating Films", Proceeding of Intern. Tribology Conf., Yokohama 1995, Satellite Forum on Tribochemistry, publ. Jap. Soc Trib., Tokyo, October 1995.
26. Smeeth, M., Gunsel, S. and Spikes, H.A. "Boundary Film Formation by Viscosity Index Improvers". Accepted for publication in Tribology Transactions, preprint no. 95-3B-TC-1.
27. Spikes, H.A. and Cann, P.M. "The Thickness and Rheology of Boundary Lubricating Layers", presented at International Tribology Conference, Yokohama, October 1995. Accepted for publication in the Proceedings.