
APPENDIX

Descriptive Data on Test Fluids and Additives

<table>
<thead>
<tr>
<th>Petroleum oil: R-620-12</th>
<th>Supplier's designation</th>
<th>R-620-12</th>
<th>Paraffinic</th>
<th>3.37x10^{-5}</th>
<th>3.50x10^{-6}</th>
<th>103</th>
<th>216</th>
<th>246</th>
<th>-15</th>
<th>1.4755</th>
<th>860.2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Symbol used in this study</td>
<td>Viscosity at 38°C (m²/s)</td>
<td>Viscosity at 99°C (m²/s)</td>
<td>Viscosity index (ASTM D-2270)</td>
<td>Flash point (°C)</td>
<td>Fire point (°C)</td>
<td>Pour point (°C)</td>
<td>Refractive index</td>
<td>Density at 20°C (kg/m³)</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

DISCUSSION

C. N. Rowe

This paper is novel in the method of extracting lubricant from the Hertzian contact zone and the subsequent analysis of properties. The results for the VI improved lubricants have practical interest since this is the first apparent demonstration that polymeric molecules breakdown under high shear rates in EHD contacts. However, the results are not totally unexpected in that polymeric oils VI improvers undergo degradation in a diesel injector nozzle shear test for which the shear rate is somewhat lower than those reported here in the sliding EHD contacts [15].

Apart from degrading the polymer in the sliding contact, there may be an additional mechanism which could contribute to the lowering of the viscosity and to the shift in the distribution of polymer molecular weights. This is the phenomenon that elastic particles in a fluid undergoing shear tend to migrate away from a wall [16, 17]; that is, there is a net diffusion transverse to the direction of flow and the flow profile in pipe flow is much flatter than the parabolic profile expected with Newtonian fluids [18]. If this phenomenon should occur in the entrance region of an EHD contact, then it is possible that the concentration of polymer in the volume of liquid next to the moving surface, which carries fluid into the contact zone, is somewhat deficient. Furthermore, the molecules of highest molecular weight would encounter the greatest stress in the shear field, and thus undergo the greatest transverse motion [17].

Examination of Fig. 6 for Fluid P6, the higher molecular weight VI improver, suggests that the molecular weight distribution peak is actually higher for the fluid in the entrance region than in the oil reservoir or original solution, in agreement with the polymer "rejection" concept. However, the areas under the curves do not appear to differ significantly from that of the original fluid, so that the experimental evidence is not at all consistent.

As often happens, a discussion of a paper suggests additional experiments. The authors apparatus is cleverly suited to obtaining answers to a number of questions of practical interest to the lubricant chemist.
Additional References

P. M. Ku and B. B. Baber

The authors have succeeded in extracting exceedingly small quantities of fluid samples from a sliding EHD conjunction and in analyzing these samples by appropriate means. The work requires painstaking care; and the authors are to be congratulated for their brilliant accomplishments.

Aside from the development of experimental techniques, the authors have presented typical results on a number of fluids subjected to rather strenuous EHD conditions—conditions fairly representative of hardware applications. These results have both theoretical and practical implications, which we propose to discuss briefly.

One intriguing aspect of the theoretical problem is the possible influence of shear degradation on the central film thickness (and particularly the minimum film thickness). We shall ignore the pressure-viscosity effect in this discussion, and assume that the central film thickness, \( h_c \), is at least as a first approximation, a power function of \( \mu V_s \), where \( \mu \) is the fluid viscosity at the conjunction inlet, and \( V_s \) is the sliding velocity which is also the sum velocity in this case. The question is whether the fluid viscosity should be that of the fresh fluid or of the sheared fluid; and that depends upon the way the system operates.

Let us first consider two limiting cases. If we assume that the fluid entering the conjunction were all fresh fluid, then we would expect approximately a power relationship between \( h_c \) and \( \mu V_s \), where \( \mu \) is the viscosity of the fresh fluid at a conjunction-inlet temperature of 25 deg C, as given in the authors’ Table 2. On the other hand, if that is not so and that the “entrance” samples in Table 2 were all permanently shear-degraded, then we would expect approximately a power relationship between \( h_c \) and \( \mu_s V_s \), where \( \mu_s \) is the viscosity of the sheared fluid at 25 deg C. The \( \mu \) and \( \mu_s \) values given in the authors’ Table 4 were determined mostly at temperatures other than 25 deg C and are not directly applicable to the experimental conjunction-inlet temperature of 25 deg C. However, as a first approximation, we might assume that the percent of viscosity change due to shear given in Table 4 would apply to 25 deg C. With this assumption, approximate values of \( \mu_s \) at 25 deg C can be obtained. Table 6 gives the values of \( \mu_s \) taken directly from Table 2 and the values of \( \mu_s \) calculated in the manner described, the corresponding values of the \( \mu_s V_s \) and \( \mu_s V_s \) products, and also the values of measured \( h_c \) given in the authors’ Table 2.

Fig. 8 plots the \( h_c \) versus \( \mu_s V_s \) and \( h_c \) versus \( \mu_s V_s \) data given in Table 6. The hollow symbols show the \( h_c \) versus \( \mu_s V_s \) behavior for wholly fresh fluids, while the solid symbols show the \( h_c \) versus \( \mu_s V_s \) behavior for wholly sheared fluids. Note that only fluids P1, S1, S5, and S9 exhibit a power-law \( h_c \) versus \( \mu_s V_s \) behavior—and they all have low molecular weights. Three of these fluids, P1, S1, and S9, do not suffer significant permanent shear degradation; and it would appear that fluid S5 would behave similarly.

Now, if it is assumed that the fluid entering the conjunction were all permanently shear-degraded, then the \( h_c \) versus \( \mu_s V_s \) behavior should follow an approximate power relationship. This appears to be the case as shown in Fig. 8, which would imply that perhaps the fluid in the reservoir might be all shear-degraded fluid in each of the authors’ tests. Yet, there seems to be a mystery, because the molecular weight distributions for the “original,” “reservoir,” and “entrance” samples given in Figs. 3 through 6 are so nearly alike. Could it be that the samples from the reservoirs were taken very early during each of the tests, so that the reservoir content was essentially fresh, rather than shear-degraded? On the other hand, if that is not so and that the “entrance” samples indeed did not suffer much permanent shear degradation, then what was controlling in the film thickness behavior? Could it be due to a temporary shear degradation occurring in the inlet region, which could not be measured by the authors’ technique?

The behavior of fluid S1, which gives \( h_c = 0.09 \mu m \) in Table 2, is interesting. Under pure rolling conditions, one would estimate \( h_c \sim 0.12 \mu m \) by the Archard-Cowking formula, which gives a 25 percent reduction in \( h_c \) due to pure sliding. We have found in our unpublished optical work as much as a 45 percent reduction in \( h_c \) due to pure sliding under comparable test conditions, with higher-viscosity fluids. Since the inlet conditions largely dominate the flow process, it would appear that this difference might be due to the effect of viscous shear in the inlet region. If that is the case, the non-Newtonian effect and nonuniform temperature distribution across the inlet film, especially in sliding, can be very important.

Another point about fluid S1 is that if \( h_c = 0.09 \mu m \), then the film thickness at the side lobes must be considerably less, probably approaching the nominal surface roughness of the ball. Did the au-


Table 7  Typical viscosity increases observed in several tests

| Test          | Viscosity Increase | Test Description | Sump Temperature | Viscosity Change | Test Duration | Sump Temperature | Viscosity Change
<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>F</td>
<td>0.02</td>
<td>Oxidation-corrosion</td>
<td>54.0</td>
<td>-</td>
<td>2.10 x 10^5</td>
<td>-</td>
<td>2.10 x 10^5</td>
</tr>
<tr>
<td></td>
<td>0.02</td>
<td>Hot-wall deposition</td>
<td>54.0</td>
<td>-</td>
<td>1.6 x 10^5</td>
<td>-</td>
<td>1.6 x 10^5</td>
</tr>
<tr>
<td></td>
<td>0.02</td>
<td>Rolling fatigue</td>
<td>54.0</td>
<td>-</td>
<td>3.10 x 10^5</td>
<td>-</td>
<td>3.10 x 10^5</td>
</tr>
<tr>
<td></td>
<td>0.02</td>
<td>Gear pitting</td>
<td>54.0</td>
<td>-</td>
<td>1.5 x 10^5</td>
<td>-</td>
<td>1.5 x 10^5</td>
</tr>
<tr>
<td></td>
<td>0.02</td>
<td>Gear pitting</td>
<td>54.0</td>
<td>-</td>
<td>1.5 x 10^5</td>
<td>-</td>
<td>1.5 x 10^5</td>
</tr>
<tr>
<td></td>
<td>0.02</td>
<td>Gear pitting</td>
<td>54.0</td>
<td>-</td>
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<tr>
<td></td>
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<td>Gear pitting</td>
<td>54.0</td>
<td>-</td>
<td>1.5 x 10^5</td>
<td>-</td>
<td>1.5 x 10^5</td>
</tr>
</tbody>
</table>

The authors observe any rubbing at the side lobes, or any abnormal local temperature behavior?

On the practical side, the authors have amply demonstrated that large permanent shear degradation has occurred with the high-molecular-weight fluids after passage through an EHD conjunction. One may visualize that in the recirculating lubrication system of practical hardware, the extent of permanent shear degradation can potentially reach a comparable level. On the other hand, the viscosity change of the total fluid content in the system is, for almost all types of hardware, also affected by oxidative degradation. So far as the EHD film thickness is concerned, the question becomes one of which form of degradation is more important. It is believed that the behavior of low-molecular-weight fluids, which are not subject to significant permanent shear degradation, may provide a limiting answer.

Table 7 presents some results on fluid F (a MIL-L-7808 synthetic lubricant), fluid E (a MIL-L-2399 synthetic lubricant), fluid C (a MIL-L-6082, Grade 1100 mineral oil), and fluid M (a MIL-L-7081, Grade 1005 mineral oil), as observed in a variety of tests using different test devices and sump temperatures. The asterisks indicate that the various tests were terminated at or soon after the respective scheduled test durations. Without going into details, it can be said that, within the range of oxidative stability of the fluids, the percent viscosity increase of samples taken from the sump as a function of time is quite well-defined; and the extent of viscosity increase, being due essentially to oxidation, is strongly influenced by the sump volume and sump temperature. Specifically, in the oxidation-corrosion, hot-wall deposition, and bearing deposition tests, the fluid is subjected to little or very modest EHD stressing. However, in addition to the controlled fluid temperature in the sump (or in the glass tube in the oxidation-corrosion test), the fluid in the bearing deposition test is also exposed to a heated surface of 260 deg C, while the fluid in the hot-wall deposition test is also exposed to a heated surface of 293 deg C. The viscosity increase behavior in these three tests generally tend to reflect this additional heating effect. In all of the other tests, no additional heating is employed, and the EHD conditions vary from moderate to very severe. Still, even in these tests, the trends are essentially dominated by oxidation. In other words, with fluids not subject to significant permanent shear degradation, used within their oxidative stability range, the viscosity increase due to oxidative degradation is generally no more than about 15 percent, the effect of which on EHD film thickness is clearly rather small.

With high-molecular-weight fluids, the viscosity change for the total fluid content in the system will depend on the combined effect of permanent shear degradation and oxidative degradation. It has been shown in the preceding paragraph that, within the oxidative stability of organic fluids, the viscosity increase due to oxidation is relatively modest. The authors have shown in their paper that the viscosity decrease due to permanent shear degradation can be very large. Thus, permanent shear degradation can potentially be a problem of concern in practical hardware.