Viscosity Loss in PFPE Lubricant for Space Applications under EHL Conditions

Sobahan Mia1), Hidekazu Komiya1), Shinichiro Hayashi1), Shigeiki Morita1), Nobuyoshi Ohno1), Shingo Obara2)

1)Department of Mechanical Engineering, Saga University
1, Honjyo-machi, Saga 840-8502, Japan
2)Japan Aerospace Exploration Agency
2-1-1, Sengen, Tsukuba-shi, Ibaraki 305-8505, Japan
*Corresponding author: sonet_eng@yahoo.com

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An unbranched perfluoropolyether (PFPE) 815Z is the current ball bearing lubricant for space applications. Measurements of elastohydrodynamic lubrication (EHL) oil film thickness have been carried out to assess the lubricating performance of PFPE with average molecular weight of 9200 using an optical interferometric technique under mean Hertzian pressure 0.45 GPa. The film thickness of 815Z became less than predicted film thickness from Hamrock and Dowson formula for EHL central film thickness. There are two main explanations why PFPE is inferior to mineral oil in their ability to form EHL films, temporary viscosity loss and permanent viscosity loss. In order to elucidate the results, measurements of permanent viscosity loss under mean Hertzian pressure from 0.41 GPa to 2.67 GPa have been carried out using the thrust ball bearing. There results show that the degree of the permanent viscosity loss depends on Hertzian pressure, occurrence of permanent viscosity loss of 36 % with 2.67 GPa and 2 % with 0.41 GPa.

Keywords: viscosity loss, PFPE, space application, thrust ball bearing, molecular decomposition, EHL

1. Introduction

Perfluoropolyether (PFPE) fluids are used on magnetic recording media1), aerospace industry and satellite instruments satisfactorily2). These fluids are also used as hydraulic fluids, high temperature liquid lubricants in turbine engines3), and base oils of high-temperature greases. Improved lubrication of the mechanical system is the key to extended satellite life, resulting in more reliable and longer operating components. Performance of the space bearings depends largely on the characteristics of the lubricant used. PFPE 815Z is a well-known ball bearing lubricant for the International Space Station. The physical properties of PFPE fluids that enable them to perform lubricating functions in severe environments are low vapor pressure, surface energy and high shear stability as well as their good thermal stability. So far, a number of studies of rolling bearing life have been developed with respect to elastohydrodynamic lubrication, especially in relation to film parameter4,5,6).

An investigation was carried out to clarify merits or demerits of lithium soap grease and paraffinic mineral base oil concerning bearing life7). Ohno et al. summarized the general tendency of base oils as follows: bearing life increases with the film parameter, and the bearing life of grease is shorter than the bearing life of base oil by oil starvation at EHL inlet region. Despite considerable research of PFPE, their effects on ball bearings have not been investigated properly. In the rolling element bearing applications the lubricant can have a marked effect on bearing life and load capacity. The general tendency of PFPE fluids shows that bearing life increases with the film parameter and at high shear rate in EHL inlet region the viscosity was decreased by mechanical shear and EHL oil film was not easily formed8). In their applications PFPE fluids go under very high pressure at elastohydrodynamic contacts. Rheology of PFPE fluids at high pressure is very important to understand their behavior in elastohydrodynamic contacts9).

Lubricants used in space mechanisms must be thoroughly tested prior to their selection for critical applications. Spacecraft designer are constantly in need of tribological data for various material/lubricant combination. So, it is important to investigate the lubricant 815Z properly since their application in space ball bearing. In this research authors inspect 815Z through various experimental processes. A used 815Z lubricant was also considered on the tests. This study showed that permanent viscosity loss occurred in fresh 815Z fluid.
Table 1  Properties of fresh fluid 815Z

<table>
<thead>
<tr>
<th>Fluid name</th>
<th>$\rho$, g/mL</th>
<th>$\nu$, mm$^2$/s</th>
<th>VI</th>
<th>$\alpha$, GPa$^{-1}$</th>
<th>$M$, g/mol</th>
</tr>
</thead>
<tbody>
<tr>
<td>288K</td>
<td>1.858</td>
<td>139.1</td>
<td>313K</td>
<td>343</td>
<td>11.9</td>
</tr>
<tr>
<td>313K</td>
<td>139.1</td>
<td>42.7</td>
<td>313K</td>
<td>343</td>
<td>11.9</td>
</tr>
<tr>
<td>373K</td>
<td>42.7</td>
<td>343</td>
<td>11.9</td>
<td>9200</td>
<td></td>
</tr>
</tbody>
</table>

2. Test Fluid

Test fluid is perfluoropolyether (PFPE) 815Z, which contains acetal group (-OCF$_2$O-). The properties of tested fluid were listed in Table 1. Where, $\rho$: density (g/mL), $\nu$: kinematic viscosity (mm$^2$/s), VI: viscosity index, $\alpha$: pressure-viscosity coefficient (GPa$^{-1}$), $M$: molecular weight (g/mol).

3. High-Pressure Rheology at Quasi-Static Condition

3.1. Viscoelastic solid transition temperature at atmospheric pressure

An air bubble is closed into a space between test fluid and a cover glass plate; its volume apparently expands as a result of contraction of the fluid by cooling. Thus expanded bubble generates tensile stresses along its interface under solidified condition. At the same time the photoelastic effect appears under a dark polarized field. This enables the stress analysis and estimation of mechanical properties of the solidified fluid. At temperature when this dark polarization occurs is known as viscoelastic solid transition temperature at atmospheric pressure ($T_{VE0}$). For fresh 815Z fluid is 167 K.

3.2. Viscoelastic solid transition temperature at high-pressure and Bulk modulus

The high-pressure density of the test fluid was done by the high-pressure densitometer shown in Fig. 1. The test fluid of 2 ml was poured into the test machine and pressure was applied in the upper plunger by a hydraulic power unit. The density was determined corresponding to the pressure by measuring the fluid volume in the machine using linear gauge. Isothermal compressibility influence was considered in the experiment.

One of the basic equations for the solidification of oil is the equation of volumetric change, which is used in the strength of materials$^{11}$. The volumetric strain $\varepsilon$ is defined as the ratio of the decrease in volume to the original volume.

$$\varepsilon = \frac{dV}{V} = \left( -\frac{\partial \ln \rho}{\partial p} \right)_T dp + \left( -\frac{\partial \rho}{\partial T} \right)_p dT$$

$= \left( -\frac{1}{K} \right) dp + 3\delta \delta T$  \hspace{1cm} (1)

where $V$ is the volume, $\rho$ is density, $p$ is pressure, $T$ is temperature, $K$ is bulk modulus and $\delta$ is coefficient of thermal expansion.

![Fig. 1 High-pressure densitometer](image)

![Fig. 2 Density-pressure curve for 815Z fluid](image)
3.3. Phase Diagram

The phase diagram of 815Z fluid is shown in Fig. 4. The equation relating the temperature to pressure at viscoelastic solid point \( T_{VE} \) is represented in the following empirical formula:

\[
T_{VE} = T_{VE0} + A_1 \ln(1 + A_2 p)
\]

where \( A_1 \) and \( A_2 \) are the parameters depending on fluid properties. For the fluid 815Z, parameters obtained are \( A_1 = 1626.2 \) K and \( A_2 = 0.075 \) GPa\(^{-1}\).

3.4. Viscosity-Pressure-Temperature Relationship

A high pressure falling body viscometer is used to determine the high-pressure viscosity up to 0.4 GPa and at temperature of 293 K and 313 K for 815Z fluid. The variation of pressure-viscosity coefficient \( \alpha \) with temperature is described by Equation (3),

\[
\alpha = C_1 + C_2 \log_{10} \nu
\]

where \( \nu \) is kinetic viscosity (mm\(^2\)/s) and \( \alpha \) is pressure-viscosity coefficient (GPa\(^{-1}\)). The parameters obtained are \( C_1 = -20.04 \) GPa\(^{-1}\) and \( C_2 = 14.91 \) GPa\(^{-1}\).

Ohno derived a very useful viscosity-pressure-temperature correlation on the basis of free volume and phase diagram\(^{12}\). The viscosity-pressure-temperature relationship is given below:

\[
\log_{10} \eta = 7 - \frac{B_1(T - T_{VE})(T_{VE0}/T_{VE})}{B_2 + (T - T_{VE})(T_{VE0}/T_{VE})}
\]

4. Viscosity loss under EHL conditions

4.1. Viscosity loss at EHL Film thickness measurements

The practical importance of the mechanism of elastohydrodynamic lubrication lies in the thickness of the oil film between the surfaces. Its thickness is controlled by the operating conditions expressed in terms of various operating parameters such as surface velocity, load and fluid viscosity\(^{13}\). The influence of these parameters on film thickness should be obvious if the basic concepts of EHL have been understood. The EHL film thickness measurement through light interferometry technique was done using rolling-sliding contact apparatus. Applied contact load was 86 N (mean Hertzian pressure 0.45 GPa) that was comprised of shaft with a bearing steel ball of 23.8 mm diameter. A pyrex glass optically flat of 45 mm diameter with 5 mm thickness was used to measure the EHL film thickness on a temperature condition of 292 K. Fig. 6 showed the relation between EHL central film thickness and rolling velocity. The solid line in the figure is the theoretical Hamrock-Dowson\(^{13}\) film thickness of 815Z.
Here, the actual film thickness measurement values (● marks in graph) of 815Z were thinner than the theoretical film thickness. There are two main explanations why film thickness of 815Z is thinner than the theoretical film thickness, temporary viscosity loss and permanent viscosity loss. In order to elucidate the results, measurements of permanent viscosity loss under mean Hertzian pressure from 0.41 GPa to 2.67 GPa have been carried out using the thrust ball bearing.

4.2. Viscosity loss at thrust ball bearing tests

The test rig is shown in Fig. 7. The inner ring was attached to an oil container housing. The outer ring was attached to a rotating spindle. The spindle was supported by angular contact ball bearings and driven by an electric motor via a belt. The load was applied by two compression springs. Tests were carried out using type 51104 thrust ball bearings. In order to change Hertzian pressure on contact surface, the number of balls was changed here from 14 to 3 and axial load were adjusted. The test conditions were outer ring speed 1000 rev/min under mean Hertzian pressure 0.41, 1.23, 1.53, 1.95 and 2.67 GPa. Temperature of the oil was measured by inserting a thermocouple in the oil container.

The changes of viscosity with operating time of tested fluids are drawn in Fig. 8 with absolute viscosity ratio \( \eta/\eta_0 \) at 313 K. The significant result is that permanent viscosity loss of fluid 815Z occurred rapidly with time at mean contact pressures of 1.95 GPa to 2.67 GPa. A mean contact pressure decreased, degree of viscosity loss decreased gradually. At the mean contact pressure of 0.41 GPa, permanent viscosity loss occurred only 2% after 673 hours experiment. The film parameter of fresh 815Z fluid at mean contact pressure of 2.67 GPa is \( \Lambda = 4 \), where as when 36% permanent viscosity loss occurred at same pressure film parameter is \( \Lambda = 3 \). The film parameter \( \Lambda = h_{\text{min}}/\sigma_r \), where \( \sigma_r \) is composite roughness and \( h_{\text{min}} \) is the minimum EHL film thickness.

Fig. 7 Bearing testing machine

Fig. 8 Viscosity changes of 815Z with operating hours

5. Discussion

The purpose of this study is to clarify the viscosity loss under EHL conditions. In the thrust ball bearing tests authors found that the permanent viscosity loss occurred in fluid 815Z. Fig. 9 shows the thrust ball bearing experimental points of Fig. 8 in phase diagram of 815Z as shown in Fig. 4. In the diagram dotted line indicates phase between viscoelastic solid and elastic-plastic solid by \( T_{\text{VE}} = T_{\text{E}} = 75 \). Experimental points A and B showing a little permanent viscosity loss at bearing test are plotted in liquid phase where as D and E showing the large permanent viscosity loss are in elastic-plastic solid region and C is plotted in viscoelastic solid region.

In the authors’ previous investigation was pointed out the decomposition mechanism of 815Z with acetal group (-OCF\(_2\)O-). For example, authors carried out FT-IR analysis about two fluids, fresh fluid of oil 815Z and used fluid of oil 815Z after experiment for 85.5 hours with 2.67 GPa. The massive change of molecular weight has been observed. Molecular weight reduced from 9200 g/mol to 5900 g/mol. It can be seen from the decomposition of 815Z. The decomposition of 815Z generates acid fluoride. Then, this fluoride was hydrolyzed to carboxylic acid and hydrogen fluoride.

By analyzing Fig. 9 with Fig. 8, the effect of solidification of the oil on permanent viscosity loss can be seen. The larger permanent viscosity loss with decomposition of 815Z occurred in elastic-plastic solid region and a little permanent viscosity loss occurred in liquid region.

Fig. 9 Experimental points in phase diagram of 815Z, point A to E from Fig. 8 and point F from Fig. 6
The experimental condition of EHL film thickness measurement shown in Fig. 6 has been plotted in Fig. 9 indicating point F. In EHL condition at lower pressure in liquid region has shown very low viscosity degradation. Therefore, 815Z fluid in the inlet region of EHL test showed temporary viscosity loss with lower film thickness as shown in Fig. 6. In case of used fluid reducing molecular weight 9200 g/mol to 5900 g/mol with permanent viscosity loss \( \eta/\eta_0 = 0.475 \) after thrust ball bearing experiment for 147 hours with 2.67 GPa as shown in Fig. 8, the results of central film thickness measurement shows (○) marks in Fig. 6. The broken line indicates theoretical film thickness of used fluid. The measured central film thickness of the used fluid agreed with the theoretical film thickness of the used fluid.

In the ball bearing test shown in Fig. 8, the permanent viscosity loss at mean Hertzian pressure 0.41GPa does not occur. Therefore, at the high shear rate area in the EHL inlet side, the viscosity of fresh fluid of 815Z with high molecular weight 9200 was decreased temporarily by mechanical shear and oil film formation was being made difficult. In case of used fluid with molecular weight 5900, temporary viscosity loss did not occur at EHL inlet zone. Bair et al.\(^\text{[10]}\) and Jones\(^\text{[1]}\) previously pointed out the shear thinning behavior in the EHL inlet zone of a linear PFPE Z25. Our experimental result is supported by their results. These results showed permanent viscosity loss occurred on Brayco815Z fluid at high pressure. Viscosity degradation increases with the change of phase of fluid from liquid to solid.

6. Conclusions

After investigation of PFPE 815Z fluid through several experiments and summarizing the results of experiments, the following conclusions are drawn.

1. The viscosity loss occurred in 815Z fluid under EHL conditions. Permanent viscosity loss and temporary viscosity loss are observed.
2. Permanent viscosity loss of 815Z fluid occurred rapidly with time at mean contact pressure of 1.95 GPa to 2.67 GPa. When mean contact pressure decreased, degree of viscosity loss decreased gradually.
3. The fluid contains acetal group (\(-\text{OCF}_2\text{O}-\)), which is the cause of permanent viscosity loss by decomposition of molecule under the high-pressure conditions.
4. Viscosity loss increases with the change of phase from liquid to elastic-plastic solid.
5. In the inlet region of EHL test, 815Z fluid showed temporary viscosity loss with lower film thickness.

7. References