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EFFECT OF PERFLUOROPOLYETHERE (PFPE) FLUIDS ON LIFE OF BALL BEARINGS

Md. Ziaur Rahman[1], **Nobuyoshi Ohno**[1] **and Hiroshi Komiya**[2]

[1]Department of Mechanical Engineering, Saga University, 1, Honjo, Saga, 840-8502, JAPAN,
[2]Koyo Seiko Co., Ltd., 24-1, Kokubu Higanjo, Kashiwara, Osaka, 582-8588, JAPAN.

ABSTRACT

The effect of Perfluoropolyether (PFPE) fluids on ball bearings fatigue life was carried out by systematic tests using thrust bearings. Three kinds of PFPE fluids type K oil (GPL105), type D oil (S200), type F oil (M25) were tested. Comparing with mineral oils, it showed that bearing life increased with film formation parameter. However, permanent viscosity declination of the type F oil (M25) was found. Elastohydrodynamic lubrication (EHD) central film thickness measurement were done by rolling EHD interferometry test rig and results were compared with the theoretical values of Hamrock-Dowson film measurement. This study showed that though type F oil (M25) was an acetal group ($-OCF_2O-$) containing PFPE fluid, at high shear rate in EHL inlet side viscosity was decreased by mechanical shear and an oil film was not easily formed. This results in an inadequate oil film formation. Thus contacts occur in bearings and shorten the bearings life thereby.

Keywords: PFPE Fluids, Lubricant Rheology, EHL Traction, Ball Bearings.

1. INTRODUCTION

Perfluoropolyether (PFPE) fluids are used on magnetic recording media, aerospace industry and satellite instruments satisfactorily [1-2]. Recently these oils have been used as hydraulic fluids, high temperature liquid lubricants in turbine engines [3], and base oils of high-temperature greases. 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. Despite considerable research on PFPE, their effects on ball bearings have not been investigated properly.

In rolling element bearing applications the lubricant can have a marked effect on bearing life and load capacity. In order to investigate the effect of Perfluoropolyether (PFPE) fluids on ball bearing fatigue life, the authors carried out systematic tests using thrust bearings, type 51104. Fifteen tests were done for each of the oils. Flaking occurred in both races and bearing cage failure occurred many times. Central film thickness was calculated by rolling-sliding machine. Oil temperature rise and coefficient of friction were investigated and analyzed. This study showed that permanent viscosity loss occurred in type F oil (M25). This viscosity was decreased by mechanical shear at high shear rate in EHL inlet side. So an oil film did not easily form. This result in an inadequate oil film formation and contacts occur in bearings and shorten the bearings life thereby.

2. EXPERIMENTAL DETAILS

2.1 Test Fluids

This study was based on three kinds of PFPE lubricants. Their names, physical properties and molecular structures are given below in Table 1. Where ρ is density, ν is kinematic viscosity, VI is viscosity index and M is molecular weight.

Table 1: Properties of PFPE fluids

Fluid	ρ, g/mL	ν, mm^2/s		VI	M
	288 K	313 K	373 K		g/mol
K (GPL105)	1.910	168.1	18.24	121	4700
D (S200)	1.886	194.6	34.72	227	8400
F (M25)	1.847	141.7	41.88	334	9500

Molecular structures:

Fluid K (GPL105): $F[C(CF_3)FCF_2O]_nCF_2CF_3$
Fluid D (S200): $F(CF_2CF_2CF_2O)_nCF_2CF_3$
Fluid F (M25): $CF_3[(OCF_2CF_2)_p(OCF_2)_q]OCF_3$

2.2 Test Rig

The test rig is shown is Fig 1. The inner ring was attached to an oil container housing. The outer ring was attached to a rotating spindle. The spindle was supported by hydrodynamic bearings and driven by an electric motor via a belt. The load is applied by two compression springs. The friction torque was measured by a strain gauge on a cantilever.

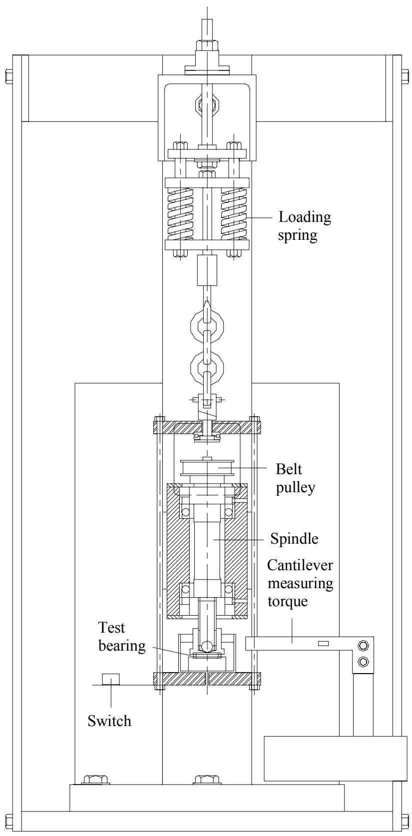

Fig 1. Bearing life test rig

2.3 Test Condition and Test Bearing

The test conditions were as follows: the rating life 11.38 h for 3 balls, outer ring speed 1000 rev/min with axial load of 4.4kN. The maximum test duration was limited to 168 hours which was equivalent to 10^7 revolutions. Temperature of the oil was measured by inserting a thermocouple in the oil container. The oil film formation was estimated by a circuit, which observed the insulative resistance between the outer and inner rings shown in Fig 2.

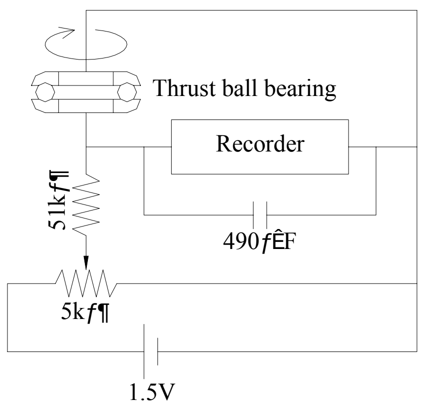

Fig 2. Circuit diagram of measuring oil film formation

The outer and inner diameters of test bearing were 35mm and 20mm respectively with a hardness of 64.2HRC. Roughness value in root mean square (r.m.s.) of the ring was 0.02μm. Bearing ball diameter was 5.556mm.

2.4 Experiment Procedure

Prior to each test, the test bearing was carefully cleaned by immersing it in an ultrasonic cleaner, rinsed in n-hexane and dried with hot air. Fifteen tests were carried out with each of the oils under the same condition. Failure was detected by vibration of a place clamped to the test machine frame. A small roller was put freely on the plate. When vibration became violent, the roller fell down from the plate and the driving source was automatically cut off.

Sizes, location of flaking and state of oxide film formation on balls or track surfaces were inspected by photometric investigation. The oil level in the oil bath was maintained at 15mm over the surface in the test bearing. Tests were carried out at ambient temperature.

3. EXPERIMENTAL RESULTS

The experimental results of the different influencing relevant factors on bearing life are listed in Table 2. An average viscosity ratio η/η_0 after and before the life test experiment, film parameter Λ and oil film formation S%, temperature rise ΔT in oil bath, coefficient of friction were shown in Table 2.

Table 2: Bearing life test results

Parameter	Test fluid		
	Fluid K	Fluid D	Fluid F
No. of failure	4	1	15
L_{10}/L_0	2.98	10.2	4.96
L_{50}/L_0	14.47	52.5	9.38
η/η_0	0.96	0.92	0.5
Λ	2.85	4.11	2.69
S%	96.6	94.7	84.1
ΔT, K	66.4	63.8	55.9
μ	0.0033	0.0028	0.0027

In Table 2, probability of survival of 90% life L_{10} of test fluids was calculated from Weibull equation. The corresponding Weibull distributions of the flaking fatigue failures are shown along with confidence bands

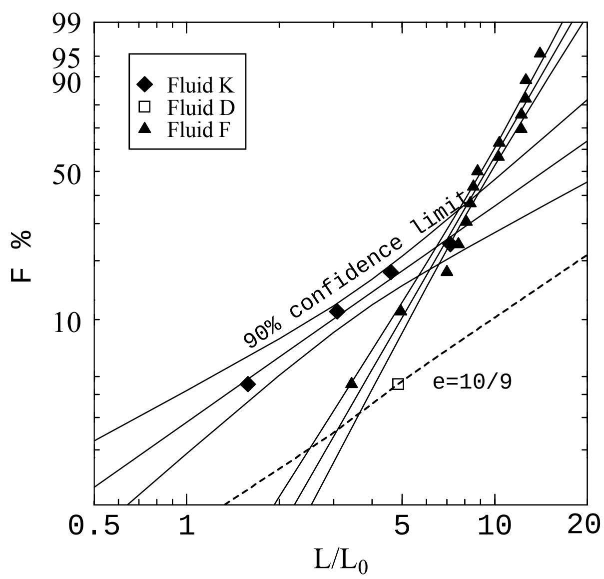

Fig 3. Weibull distribution of test fluids

in Fig. 3. Fifteen failures were recorded out of fifteen for Fluid F occurred by flaking in ball, cage and the rings. It shows higher Weibull slop. Four tests were failed in Fluid K. Fluid D showed good results and failed test was only one with L_{10} life of 10.2. Ball bearing Weibull slop (e=10/9) is taken as a dot line in Fig. 3 for comparison.

4. DISCUSSION

All the tests have been failed in Fluid F (100%) but only one test has been failed in Fluid D (6.7%). Moreover Fluid F showed viscosity declination. To investigate this phenomenon viscosity measurement of after experiments fluids were done. The changes of viscosity with time of the tested fluids are drawn in Fig. 4 with the absolute viscosity ratio η/η_0 at 313K. Viscosity degradation

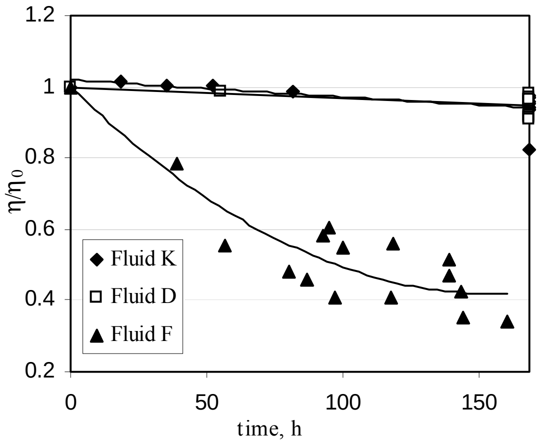

Fig 4. Viscosity changes with experiment hours

change is very noticeable in life tests of Fluid F which showed one third of the new oil viscosity after 150 hours operation. This phenomenon did not shown by Fluid K and Fluid D.

To investigate the cause of permanent viscosity loss, the EHL film thickness measurement through light interferometry technique was done using rolling/sliding contact apparatus. Contact load applied was 86 N (average Hertz pressure 0.9 GPa) that was comprised of a shaft with a bearing steel ball of 23.8 mm diameter. An optically flat sapphire of 45 mm diameter with 5 mm thickness was used to measure the EHL film thickness on a temperature condition of 292K. It was found that film thickness of fluids under the same speed condition states in the order of Fluid K >Fluid D> Fluid F.

The result for Fluid F was affected by the change in viscosity. The result of Fluid F was examined and compared with the theoretical film thickness value of Hamrock-Dowson. EHL central film thickness relationship of Fluid F with different speeds was shown in Fig. 5. The solid line in the figure is the theoretical Hamrock-Dowson film thickness of the new oil before experiment. The actual measured film thickness value (black triangle points in graph) of the new oil was about 75% of the theoretical value. But when the declined viscosity was considered the η/η_0 value was only 0.66. It shows that 34% of the viscosity was decreased in the high shear rate area in the EHL inlet side. The η/η_0 for the used oil of the life tests was 0.5 which is plotted in the Fig. 5 as blank block points. This permanent viscosity loss occurred due to mechanical shear and hydrolysis etc. Here the effect on Fluid F is might be due to mechanical shear at the inlet of EHD contact in ball bearing.

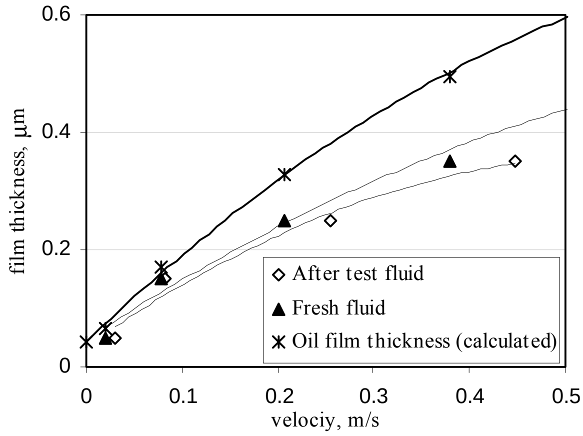

Fig 5. EHL film thickness of Fluid F

At this point, rheological differences between different PFPE fluids are considered. The relation between 90% bearing life L_{10} and film formation S% with film parameter Λ is drawn in Fig. 6 and Fig. 7 respectively. Mineral oils results [4] are also plotted for the comparison in the figures. Film parameter was

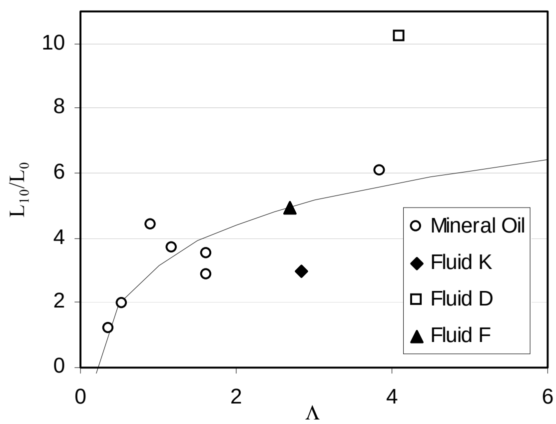

Fig 6. 90% bearing life L_{10} with film parameter Λ

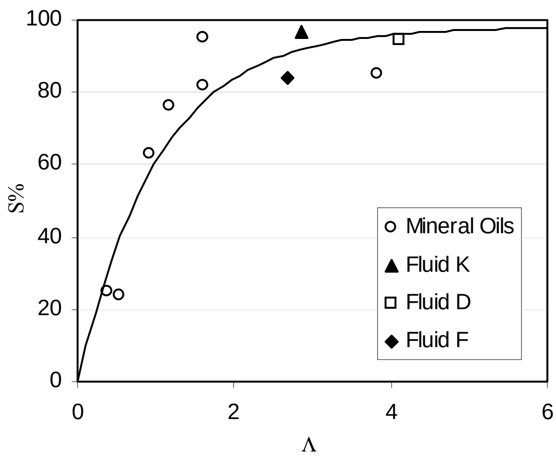

Fig 7. Separation S% with film parameter Λ determined as EHL film thickness / composite roughness

($\Lambda = h_{min}/\sigma_r$, where σ_r was taken as 0.025×10^{-6} m). The minimum film thickness h_{min} was calculated by using Hamrock-Dowson formula [5]. Fig. 6 and Fig. 7 show that the results of PFPE fluids are correlated with the mineral oils curve and bearing life L_{10} and oil film formation S% both increase in film parameter increase for both Fluid K and Fluid D. Fluid F has Λ and S% is 2.69 and 84.1 respectively. Fluid D has Λ= 4.11 and S% = 94.7. However, figures show the poor performance of Fluid F. Though Fluid F is a fluorine containing oil, at the high shear speed area in the EHL inlet side viscosity was decreased by mechanical shear and oil film formation was being made difficulty. This results in an inadequate oil film formation. Thus contacts occurred between bearings and shorten their life correspondingly.

At high pressure rheology, phase diagram of the PFPE fluids shows different lines. This phase diagram distinguishes between liquid, viscoelastic solid and elastic-plastic solid which depend on their molecular structure shown in Fig. 8 [6]. It shows that Fluid F has better low temperature performance than other oils.

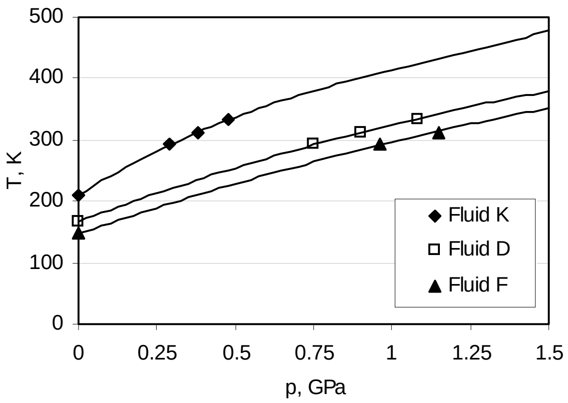

Fig 8. Phase diagram of PFPE Fluids

Viscoelastic solid transition temperature T_{VE} was considered. Molecular packing parameter T_{VE}-T is a very important parameter. Fluid K, Fluid D and Fluid F showed T_{VE}-T as 148K, 55 and 34 respectively. T was taken as the oil bath temperature. This molecular packing parameter is the discriminating factor of the solidified states of oils, i.e., for liquid $0 > T_{VE}-T$, for viscoelastic solid $0 < T_{VE}-T < 50$, and for elastic plastic solid $50 < T_{VE}-T$ [7]. So, in PFPE bearing life tests, Fluid K showed its state in viscoelastic solid region, however in case of other two fluids, their status was in elastic plastic solid region. In this elastic plastic region, friction become obvious and it increases oil bath temperature and finally shortens the bearing life. In Fluid K all were tests failed.

Fig. 9 shows a relationship between oil bath temperature rise with the coefficient of friction. Oil bath temperature increases with coefficient of friction increases. Fluid K showed maximum oil bath temperature rise ΔT with a maximum coefficient of friction μ. This temperature rise with friction depends on the spin in the ball-race contact point in the operation. Fig. 10 illustrates the velocity profile acting on a ball bearing loading due to spin. The maximum PV value that

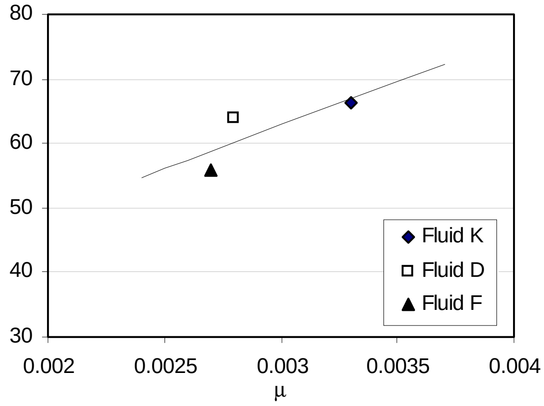

Fig 9. Coefficient of friction and oil temperature relation

exert in the tests was equal to $x = a/\sqrt{2}$. $P_{max} = 4.0$GPa. Here, P was calculated 2.82 GPa at x = 0.699mm, ω = 52.4 rad/s and velocity V was determined 0.037 m/s. Considering this velocity and pressure, total temperature rise in the ball race contact was determined from the following equation [8], $\Delta T = 46.99 P^{2.02} V^{0.53}$. Total temperature rise ΔT was found 66K.

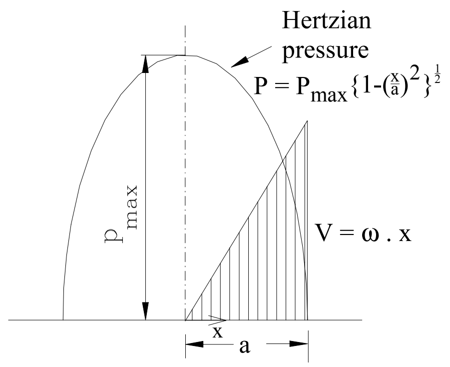

Fig 10. Pressure-viscosity relation at Hertzian contact

In the actual operation this temperature rise appears in the maximum PV point in the bearing, thus coefficient of friction become very high and flaking occurs in ball bearing point contacts.

Finally it is analyzed that, Fluid K showed the maximum oil temperature rise and thereby showed high coefficient of friction. Its state was in elasticplastic solid region thus the oil film formation was high and viscosity degradation did not occur. In case of Fluid D, its status is close to viscoelastic solid states. Temperature rise and friction is moderate thus showed good film formation and bearings life performance was very good. In Fluid F, all tests failed but oil bath temperature was lower compared with other PFPE fluids. However, as it showed viscoelastic status of oil, friction occurs and then viscosity degradation occurred and finally shortened its life poorly. Degree of viscosity degradation depends on their molecular structure. It is showed that all PFPE oils have the similar molecular structure but still they possess different characteristics in ball bearing lubrication. Moreover, permanent viscosity declination occurred in Fluid F and it showed poor EHL film thickness.

5. CONCLUSION

This study carried out a full test of three kinds of PFPE fluids ball bearing life tests and their performances were analyzed. Study showed that fluorine containing oils, PFPE, showed a tendency of having the same as the oil film formation S% and the relations of film parameter Λ with mineral oils. Their performance depends highly on their molecular structure.

These fluids performance depended on coefficient of friction, oil temperature rise and viscosity. Fluid D showed better performance than other PFPE fluids. Fluid K showed elastic plastic solid state in the tests; friction occurred with the oil temperature rise and shortens bearing life. Permanent viscosity loss occurred in Fluid F during the tests. Though Fluid F was a fluorine containing oil, at the high shear speed area in the EHL inlet side viscosity was decreased by mechanical shear and oil film formation was being made difficulty. This resulted in an inadequate oil film formation. Thus contacts occur between bearings and shorten their life correspondingly.

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