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ELASTOHYDRODYNAMIC FILM THICKNESS MEASUREMENTS WITH ADVANCED ESTER, FLUOROCARBON, AND POLYPHENYL ETHER LUBRICANTS TO 589 K (600° F)

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16. Abstract

Elastohydrodynamic (EHD) film thicknesses have been measured, by means of an X-ray technique, under conditions that closely simulate the ball-race contact in advanced turbine engine thrust bearings. The experiments were conducted with a rolling-disk machine using disks which yield a contact zone similar to that in the actual bearing. Both the rolling and spinning motions of the ball relative to the race were simulated by the apparatus. Four lubricants were evaluated at temperatures to 589 K (600° F) and maximum Hertz stresses to 2.42×10^{9} N/m^{2} (350 000 psi). The X-ray film thickness data correlated well with observations of surface distress (or lack thereof) in full-scale bearing tests with the same lubricants under similar conditions of temperature and load. The predicted variation of film thickness with speed and viscosity was verified, although the magnitude of measured film thickness was generally one-half to one-third of predicted values. An effect of stress greater than predicted was consistently observed in the higher stress range.

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ELASTOHYDRODYNAMIC FILM THICKNESS MEASUREMENTS WITH ADVANCED ESTER, FLUOROCARBON, AND POLYPHENYL ETHER LUBRICANTS TO 589 K (600° F)

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SUMMARY

Elastohydrodynamic (EHD) film thickness measurements were made in an X-ray rolling-disk machine with three lubricants: an advanced ester, a fluorocarbon, and a polyphenyl ether. The results were compared to those previously obtained with a synthetic paraffinic oil. Disk temperature was varied from 339 to 589 K (150° to 600° F). Load was varied such that the calculated maximum Hertz stress ranged from 0.69×10^9 to 2.4×10^9 newtons per square meter (100 000 to 350 000 psi). Shaft speeds of 5000 to 20 000 rpm gave surface speeds from 9.4 to 37.6 meters per second (370 to 1480 in./sec). Crowned disks both with and without a 10° cone angle were used. A nitrogen atmosphere was maintained around the disks to minimize oxidation of the lubricants.

Measured film thicknesses were less than predicted by EHD theory for all four lubricants. At a maximum Hertz stress of 1.38×10^9 newtons per square meter (200 000 psi), the measured film thicknesses were in a band centered at about one-half the predicted values. At 2.07×10^9 newtons per square meter (300 000 psi), the measured values in this band were approximately one-third of the predicted values. The variation of film thickness with the speed-viscosity parameter $(\mu_0 \alpha u/R_x')^{0.74}$ was similar to that predicted by EHD theory.

For a given value of the speed-viscosity parameter, the thickest films were measured with the fluorocarbon. The other three lubricants gave similar film thickness curves at values slightly below those for the fluorocarbon.

The effect on film thickness of increasing stress was greater than predicted by EHD theory for maximum Hertz stress above 1.38×10^9 newtons per square meter (200 000 psi). Below this stress, the theoretical relation, $h_0 \propto S_{max}^{-0.22}$ was generally verified.

The film thickness measurements correlated well with observation of surface distress (or lack thereof) in tests with 120- and 25-millimeter-bore ball bearings with the same lubricants. In general, at conditions of load and temperature where low film thicknesses were measured in the X-ray machine (of the order of a few microinches), significant surface damage was encountered in the bearing tests.

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INTRODUCTION

A primary function of a liquid lubricant in a rolling-element bearing is to form a film separating the two surfaces in rolling contact. This film, which is referred to as an elastohydrodynamic (EHD) film, is formed by the combination of the hydrodynamic action of the lubricant and the elastic behavior of the contacting surfaces. The thickness of this EHD film is typically of the order of a few microinches to something less than 100 microinches (250×10^{-6} cm). This film thickness depends on the lubricant viscosity, the bearing geometry, and such operating conditions as load and speed. The lubricant viscosity is dependent on temperature, pressure, and possibly shear rate. Predictions and measurements of elastohydrodynamic film thickness have been the subject of much research and analysis. A monograph by Dowson and Higginson (ref. 1) documents the bulk of the theoretical and experimental work that had been performed in this area until about 1964.

Bearing temperatures in the range of 478 to 589 K (400° to 600° F) are anticipated in advanced gas turbine engines and accessory drive systems such as those related to high-performance supersonic aircraft (ref. 2). Severe speed conditions are also anticipated for main-shaft thrust bearings in these engines. Reliable bearing-lubrication systems are required for these and other high-temperature, high-speed applications. New classes of liquid lubricants are being studied for these applications to determine their thermal stability, their oxidation and corrosion resistance, and their effect on rolling-element fatigue (refs. 3 to 9).

In references 7 and 8, groups of 120-millimeter-bore, angular-contact ball bearings were fatigue tested at 12 000 rpm and a temperature of 589 K (600° F) with three advanced lubricants. For a synthetic paraffinic oil and a fluorocarbon, bearing lives at 589 K (600° F) exceeded Anti-Friction Bearing Manufacturers Association (AFBMA) predicted (catalog) lives by factors greater than 13 and 3, respectively. For a polyphenyl ether, bearing life at 589 K (600° F) was less than AFBMA life.

Each of three lubricants was operating near its elastohydrodynamic temperature and load limits in these tests. Each lubricant was tested at an applied load which allowed long-term operation at 589 K (600° F) without excessive wear and surface distress in the bearings. The synthetic paraffinic oil with a antiwear additive was capable of carrying a greater load than the other two lubricants. Also, considerably less surface asperity interaction occurred with this lubricant.

Bearing tests such as those described in references 6 to 8 are very expensive and time consuming. With the use of a rolling-disk machine and a means of measuring the lubricant EHD film thickness between the disks, it is anticipated that temperature and load limitations for a particular lubricant can be determined relatively inexpensively without extensive testing. The geometry of the disks must be such that the contact area and roll and slip velocities of the ball-race contact in a bearing are simulated. Such a facility has been developed (ref. 10) which simulates the ball - inner-race contact of a 120-millimeter-bore, angular-contact ball bearing with consideration given to geometric, dynamic, elastic, thermal, and hydrodynamic effects.

Film thickness measurements with this rolling-disk machine using an X-ray transmission technique are reported in reference 11. Tests were run with a synthetic paraffinic oil both with and without an antiwear additive at temperatures to 589 K (600° F). The measured film thicknesses correlated well with observations of surface distress (or lack thereof) in full-scale bearing tests with the same lubricant under similar conditions.

The research reported herein was conducted

(1) To determine the EHD film thickness with a fluorocarbon, a polyphenyl ether, and a type II ester at temperatures to 589 K (600° F) under a variety of load and speed conditions

(2) To compare these results with existing EHD theory, similar film thickness measurements with a synthetic paraffinic oil without additives, and observations of bearings tested under similar conditions of temperature, stress, and speed

In order to accomplish the first objective, EHD film thickness measurements were made in an X-ray rolling-disk machine with the three lubricants. Disk temperatures were varied from 339 to 589 K (150° to 600° F). Load was varied such that the calculated maximum Hertz stress varied from 0.69×10^9 to 2.42×10^9 newtons per square meter (100 000 to 350 000 psi). Shaft speeds of 5000 to 20 000 rpm yielded surface speeds from 9.4 to 37.6 meters per second (370 to 1480 in./sec). AISI M-50 steel crowned disks were used both with and without a 10° cone angle. Nitrogen blanketing was used in all tests to provide a low oxygen environment and to minimize lubricant oxidation. All tests were conducted at Battelle Columbus Laboratories, under NASA Contract NAS3-11152.

SYMBOLS

a	major semiaxis of Hertzian contact, m (in.)
b	minor semiaxis of Hertzian contact, m (in.)
E_1, E_2	modulus of elasticity of elements 1 and 2, N/m^2 (psi)
E'	$\left(\dfrac{1 - \nu_1^2}{\pi E_1} + \dfrac{1 - \nu_2^2}{\pi E_2}\right)^{-1}$, N/m^2 (psi)
h_o	minimum film thickness, m (in.)
m, n, p	exponents

R_1, R_2	radius of elements 1 and 2 in rolling direction, m (in.)
R'_x	$\left(\frac{1}{R_1} + \frac{1}{R_2}\right)^{-1}$, m (in.)
S_{max}	maximum Hertz stress, N/m^2 (psi)
u	$\frac{1}{2}(u_1 + u_2)$, m/sec (in./sec)
u_1, u_2	surface velocities of elements 1 and 2, m/sec (in./sec)
w	load, N (lb)
α	pressure-viscosity coefficient, m^2/N (in.^{2}/lb)
μ_o	ambient viscosity, N-sec/m^2 (lb-sec/in.^{2})
ν_1, ν_2	Poisson's ratio of elements 1 and 2

APPARATUS AND PROCEDURE

X-ray Disk Machine

The disk machine used in this study is shown pictorially in figure 1 and is described

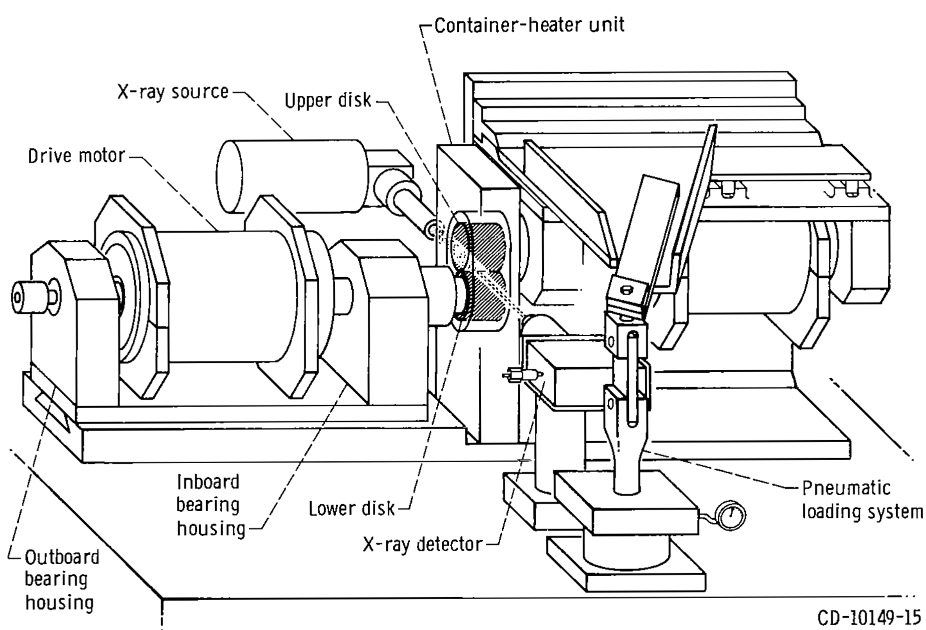


Figure 1. - Rolling-contact disk machine.

in detail in reference 10. Each of the two contacting disks is driven by a 5-horsepower, variable-speed, high-frequency induction motor. The disks are integral with the motor shafts, which are supported by precision duplex ball bearings. These support bearings are lubricated and cooled by a jet lubrication system. Disk loading is accomplished through a cantilever beam actuated by a pneumatic cylinder. Adjustment devices allow accurate positioning of the disks with respect to the X-ray alinement.

Lubricant for the disks is circulated by a pump submerged in the oil sump and is fed to the contact zone by an oil jet. The lubricant is scavenged by a gravity return to the sump. Before entering the contact zone, the lubricant is filtered and preheated. The disks are enclosed in a container-heater unit designed to operate above 589 K (600° F). A nitrogen atmosphere is maintained in the container to minimize oxidation of the lubricant.

Disks

The geometry of the disks is shown in figure 2. The design of these disks is the result of an analytical simulation study (ref. 10). The contact between the two disks closely simulates the ball - inner-race contact of a 120-millimeter-bore, angular-contact ball bearing. Crowned disks (without the 10° cone angle) were also used. The crowned-cone disks developed a spinning-rolling contact which simulates the spinning and rolling in a ball-race contact.

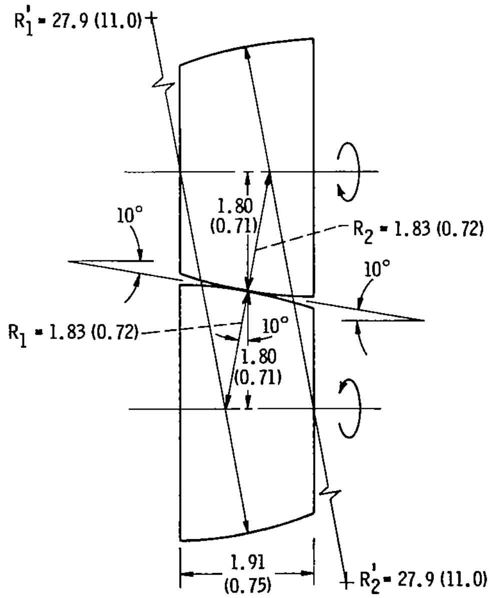


Figure 2. - Contacting disk geometry. (All linear dimensions in cm (in.).)

The disks are made of AISI M-50 steel. They are finish lapped after mounting to a surface finish of 2.5×10^{-6} to 5.0×10^{-6} centimeter (1 to 2 μin.) rms.

Instrumentation

The X-ray technique used for measuring film thickness consists essentially of flooding the contact region with X-rays and counting those transmitted by the film. Since the X-rays find the steel opaque and are absorbed only slightly by the lubricant, a count of transmitted X-rays by a scintillation counter can be calibrated to find the film thickness. X-rays are projected in the rolling direction and only a narrow band in the axial direction of 0.025 centimeter (0.01 in.) width is counted. By shifting the band axially, complete axial profiles of film thickness can be found. Care is taken to assure that X-rays are not lost through misalinement of the disks. The X-ray measurements of film thickness are generally reproducible within 2.5×10^{-6} centimeter (1 μin.) or 10 percent, whichever is greater.

Disk temperature was measured by thermocouples located at the sides of the disks near the crowned surface. Oil-in temperature was measured and maintained within a few degrees of the disk temperature.

Lubricants

The lubricants chosen for this program are of interest for bearing applications from 478 to 589 K (400° to 600° F). Properties of the test lubricants are given in table I. Viscosity-temperature characteristics are shown in figure 3.

Fluorocarbon. - The fluorocarbon is a polymeric perfluorinated polyether fluid with high oxidative and thermal stability (refs. 12 and 13). It has disadvantages of high density and low thermal conductivity. Also, at temperatures above 561 K (550° F), this fluid has a tendency to chemically attack some iron-base materials, such as ASTM 4340. However, AISI M-50, the disk material for these tests, exhibited good corrosion resistance with this fluid to 589 K (600° F) (ref. 8).

Polyphenyl ether. - The 5P4E polyphenyl ether contained an oxidation inhibitor. This lubricant has good oxidative and thermal stability (ref. 14) but relatively poor viscosity-temperature characteristics (fig. 3).

Type II ester. - The type II ester is a tetraester-base oil containing additives which include oxidation and corrosion inhibitors and an antiwear additive. This lubricant has given good results in unpublished bearing tests at temperatures to 491 K (425° F) in an air environment.

TABLE I. - PROPERTIES OF TEST LUBRICANTS

Property	Lubricant designation			
	Type II ester	Fluorocarbon	Polyphenyl ether	[a]Synthetic paraffinic oil
Additives	Oxidation inhibitor; corrosion inhibitor; antiwear additive	None	Oxidation inhibitor	None
Kinematic viscosity, cS (or 10^{-6} m^2/sec):				
At 233 K (-40° F)	8900	>100 000	>100 000	>100 000
At 311 K (100° F)	29.0	298	358	443
At 372 K (210° F)	5.4	29.8	13.0	39.7
Flash point, K (°F)	533 (500)	None	555 (540)	542 (515)
Autoignition temperature, K (°F)	716 (830)	None	886 (1135)	703 (805)
Specific gravity at 478 K (400° F)	0.85	1.59	1.05	0.74
Pressure-viscosity coefficient at 298 K (77° F), m^2/N (psi^{-1})	[b]1.1×10^{-8} (0.73×10^{-4})	[b]2.9×10^{-8} (1.99×10^{-4})	[c]1.7×10^{-8} (1.2×10^{-4})	[b]1.3×10^{-8} (0.92×10^{-4})

[a]From ref. 11.
[b]From ref. 21.
[c]From ref. 26.

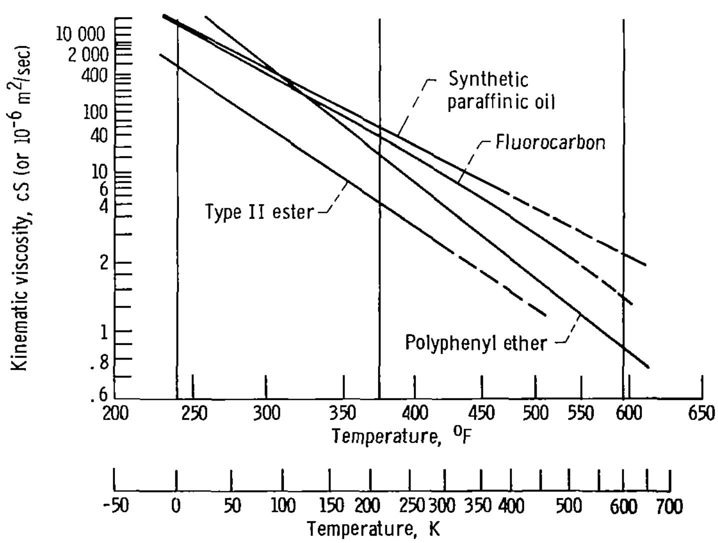


Figure 3. - Viscosity of experimental lubricants as function of temperature.

Procedure

The loading mechanism is calibrated by using a load cell in place of the lower disk. Following careful alinement of the disks both statically and dynamically, a calibration of the X-ray measuring system is performed.

Calibration of the X-ray measuring system is obtained by separating the disks by means of a precise adjusting screw in 250×10^{-6}-centimeter (100-μin.) increments, and observing the X-ray count of the known separation. The calibration was performed with each of the lubricants to compensate for difference in X-ray absorption. Film thickness measurements are performed at each stable operating condition of speed, load, and disk temperatures. For each condition, X-ray counts are averaged over 15 seconds.

Theoretical EHD Film Thickness

Theoretical solutions for elastohydrodynamic film thickness all take the general form

$$h_o \propto \frac{\mu_o^n u^m}{w^p} \tag{1}$$

where

h_o	film thickness
μ_o	viscosity at atmospheric pressure
u	surface speed
w	load
n, m, p	exponents

Theories have been developed for line contact (refs. 1 and 15) and for point contact (refs. 16 and 17). The contact between the disks used in the present investigation is elliptical with $b/a = 5.9$, where b is the semiaxis of the contact ellipse perpendicular to the rolling direction. In reference 17, for ellipses with $b/a \geq 5$, line contact is assumed. The film thickness equation for line contact (ref. 17) is

$$\frac{h_o}{R'_x} = 1.47\left(\frac{\mu_o \alpha u}{R'_x}\right)^{0.74}\left(\frac{S_{max}}{E'}\right)^{-0.22} \tag{2}$$

The theory presented in reference 16 predicts films about 15 percent thinner than predicted by the theory of equation (2); but the exponents on the speed, viscosity, and stress terms are identical. Equation (2), based on reference 17, is thus considered typical of existing elastohydrodynamic theory and will be used for comparison with measured film thickness. The pressure-viscosity coefficient α is considered constant for a given lubricant throughout the range of test conditions. It is recognized that α varies with temperature, but definitive published data for these lubricants are not available.

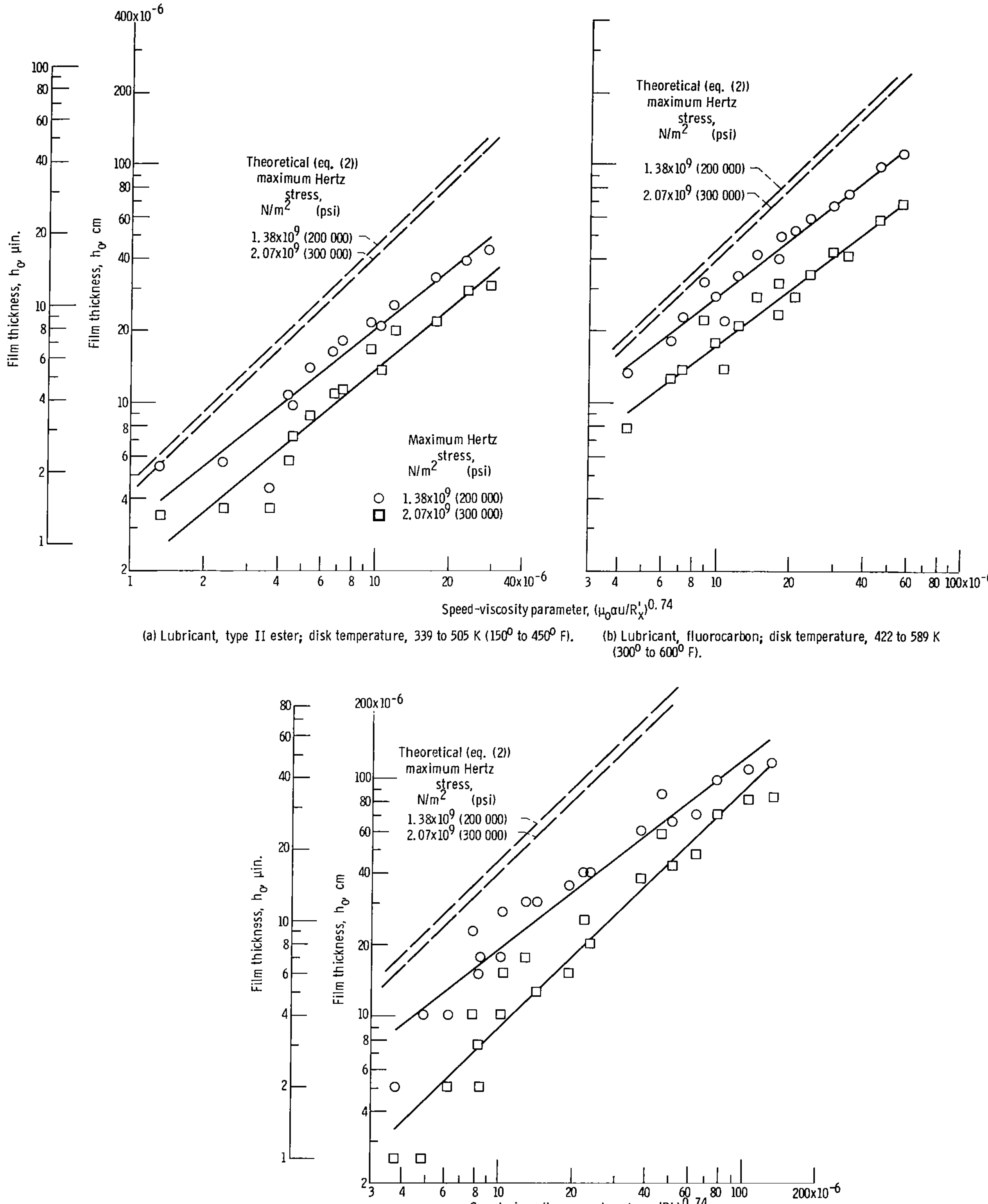
RESULTS AND DISCUSSION

Experimental Results

The measured minimum film thicknesses between crowned-cone disks with the type II ester and the fluorocarbon are presented in figures 4(a) and (b), respectively. Film thickness is plotted as a function of the speed-viscosity parameter $(\mu_0 \alpha u/R_x')^{0.74}$. Also shown, in figure 4(c), are data from reference 11 for the synthetic paraffinic oil. The experimental data are compared with equation (2). The measured film thicknesses are consistently less than those predicted by equation (2) for all the lubricants. For the fluorocarbon and the type II ester, the slope of the experimental data is only slightly less than predicted by equation (2). These results are very similar to those shown in figure 4(c) (ref. 11) for the synthetic paraffinic oil for values of $(\mu_0 \alpha u/R_x')^{0.74}$ to approximately 3×10^{-5}.

Table II presents measured film thicknesses with the ester for both the crowned-cone disks and the crowned disks. At 339 K (150° F), the film thicknesses with crowned-cone disks are slightly less than those with the crowned disks. However, there appears to be little effect, in general, of the different disk geometries on measured film thickness. The additional relative sliding in the disk contact due to the 10° cone angle apparently has little or no effect on film thickness with this lubricant. Similar results were observed with the synthetic paraffinic oil in reference 11. Preliminary tests with the fluorocarbon indicated a somewhat thinner (approximately 15 percent) film measured with crowned-cone disks than with crowned disks.

Film thickness measurements taken with the polyphenyl ether and crowned-disks are shown in figure 5. Preliminary tests with this lubricant comparing crowned disks with crowned-cone disks showed no effect of the different disk geometries. It was therefore considered reasonable to compare film thickness data with the polyphenyl ether using crowned disks with the other lubricants where the bulk of the data were taken with crowned-cone disks. The data in figure 5 also show the trend of lower-than-predicted



(a) Lubricant, type II ester; disk temperature, 339 to 505 K (150° to 450° F).

(b) Lubricant, fluorocarbon; disk temperature, 422 to 589 K (300° to 600° F).

(c) Lubricant, synthetic paraffinic oil; disk temperature, 339 to 505 K (150° to 450° F). (Data from ref. 11).

Figure 4. - Measured minimum film thickness as function of speed-viscosity parameter. Crowned-cone disks.

TABLE II. - MEASURED MINIMUM FILM THICKNESS BETWEEN DISKS WITH AN ADVANCED TYPE II ESTER LUBRICANT

(a) SI units

Disk speed, rpm	Maximum Hertz stress, N/m^2	Disk temperature, K							
		339		366		422		505	
		Crowned disks	Crowned-cone disks	Crowned disks	Crowned-cone disks	Crowned disks	Crowned-cone disks	Crowned disks	Crowned-cone disks
		Measured minimum film thickness, h_o, cm							
5 000	1.04×10^{9}	28×10^{-6}	23×10^{-6}	10×10^{-6}	10×10^{-6}	5×10^{-6}	5×10^{-6}	------	------
	1.38	23	20	8	10	5	5	2×10^{-6}	5×10^{-6}
	1.72	20	18	5	8	2	5	------	------
	2.07	15	13	5	8	2	2	------	------
	2.47	10	10	5	5	2	2	------	------
10 000	1.04×10^{9}	41×10^{-6}	38×10^{-6}	18×10^{-6}	20×10^{-6}	8×10^{-6}	10×10^{-6}	------	------
	1.38	36	33	15	18	8	10	------	5×10^{-6}
	1.72	30	28	10	13	8	8	------	5
	2.07	25	20	10	10	5	5	------	2
	2.47	18	15	8	8	5	5	------	------
15 000	1.04×10^{9}	48×10^{-6}	41×10^{-6}	23×10^{-6}	23×10^{-6}	13×10^{-6}	15×10^{-6}	------	------
	1.38	46	38	23	20	10	13	------	5×10^{-6}
	1.72	41	36	18	20	10	10	------	------
	2.07	33	28	13	15	8	8	------	------
	2.47	23	18	13	10	5	5	------	------
20 000	1.04×10^{9}	53×10^{-6}	48×10^{-6}	30×10^{-6}	25×10^{-6}	15×10^{-6}	18×10^{-6}	------	------
	1.38	53	43	28	25	15	15	8×10^{-6}	5×10^{-6}
	1.72	46	36	20	23	15	13	8	5
	2.07	38	30	18	20	10	10	5	2
	2.47	30	20	15	13	8	8	------	------

TABLE II. - Concluded. MEASURED MINIMUM FILM THICKNESS BETWEEN DISKS WITH AN ADVANCED TYPE II ESTER LUBRICANT

(b) U. S. Customary units

Disk speed, rpm	Maximum Hertz stress, psi	Disk temperature, $^{\circ}F$							
		150		200		300		450	
		Crowned disks	Crowned-cone disks	Crowned disks	Crowned-cone disks	Crowned disks	Crowned-cone disks	Crowned disks	Crowned-cone disks
		Measured minimum film thickness, h_0, μin.							
5 000	150 000	11	9	4	4	2	2	--	--
	200 000	9	8	3	4	2	2	1	2
	250 000	8	7	2	3	1	2	--	--
	300 000	6	5	2	3	1	1	--	--
	350 000	4	4	2	2	1	1	--	--
10 000	150 000	16	15	7	8	3	4	--	--
	200 000	14	13	6	7	3	4	--	2
	250 000	12	11	4	5	3	3	--	2
	300 000	10	8	4	4	2	2	--	1
	350 000	7	6	3	3	2	2	--	--
15 000	150 000	19	16	9	9	5	6	--	--
	200 000	18	15	9	8	4	5	--	2
	250 000	16	14	7	8	4	4	--	--
	300 000	13	11	5	6	3	3	--	--
	350 000	9	7	5	4	2	2	--	--
20 000	150 000	21	19	12	10	6	7	--	--
	200 000	21	17	11	10	6	6	3	2
	250 000	18	14	8	9	6	5	3	2
	300 000	15	12	7	8	4	4	2	1
	350 000	12	8	6	5	3	3	--	--

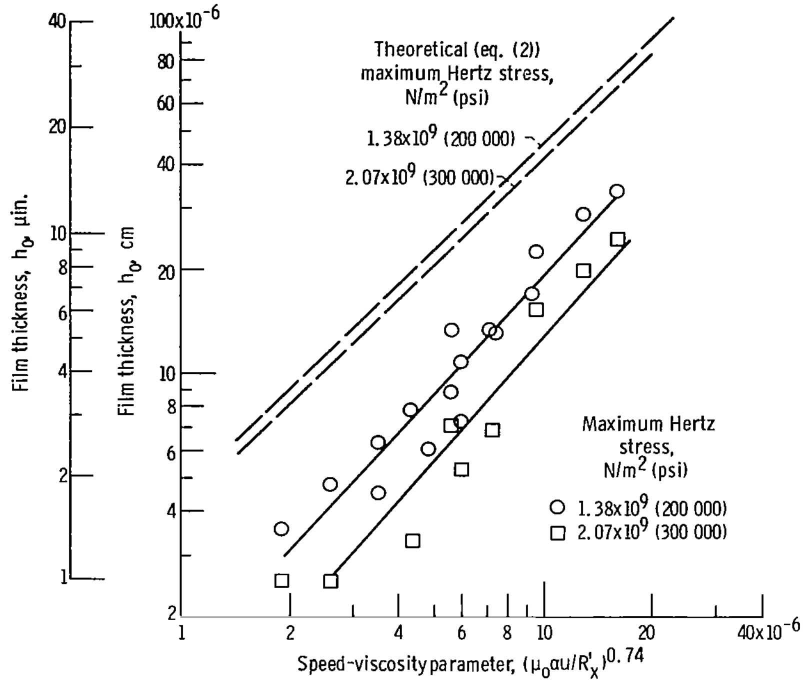


Figure 5. - Measured minimum film thickness between crowned disks with polyphenyl ether, as function of speed-viscosity parameter.

film thicknesses. Also, the experimental slope is similar to the predicted slope, although the greater scatter in the low-film-thickness region tends to steepen the slope to greater than predicted.

A comparison of film thickness measurements with the four lubricants is shown in figure 6 for a maximum Hertz stress of 1.38×10^9 newtons per square meter (200 000 psi). All experimental curves lie within a band centered at approximately one-half of the film thickness predicted by equation (2). For 2.07×10^9 newtons per square meter (300 000 psi), this band was centered at about one-third of the predicted magnitude. Considering all the data for all the lubricants, the 0.74 exponent on the speed-viscosity parameter is in general confirmed. For a given value of the speed-viscosity parameter, the fluorocarbon gave the thickest measured EHD films.

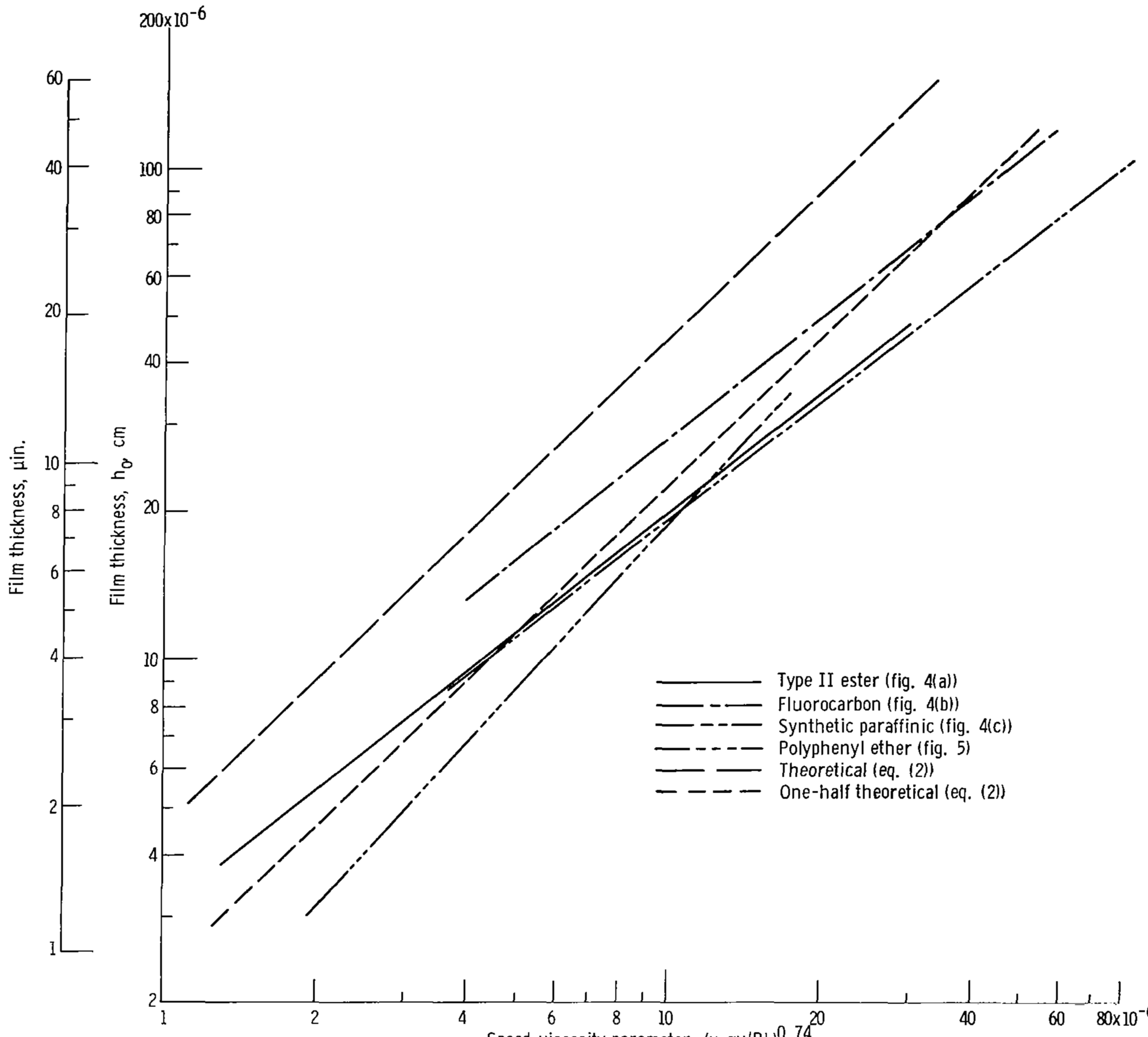
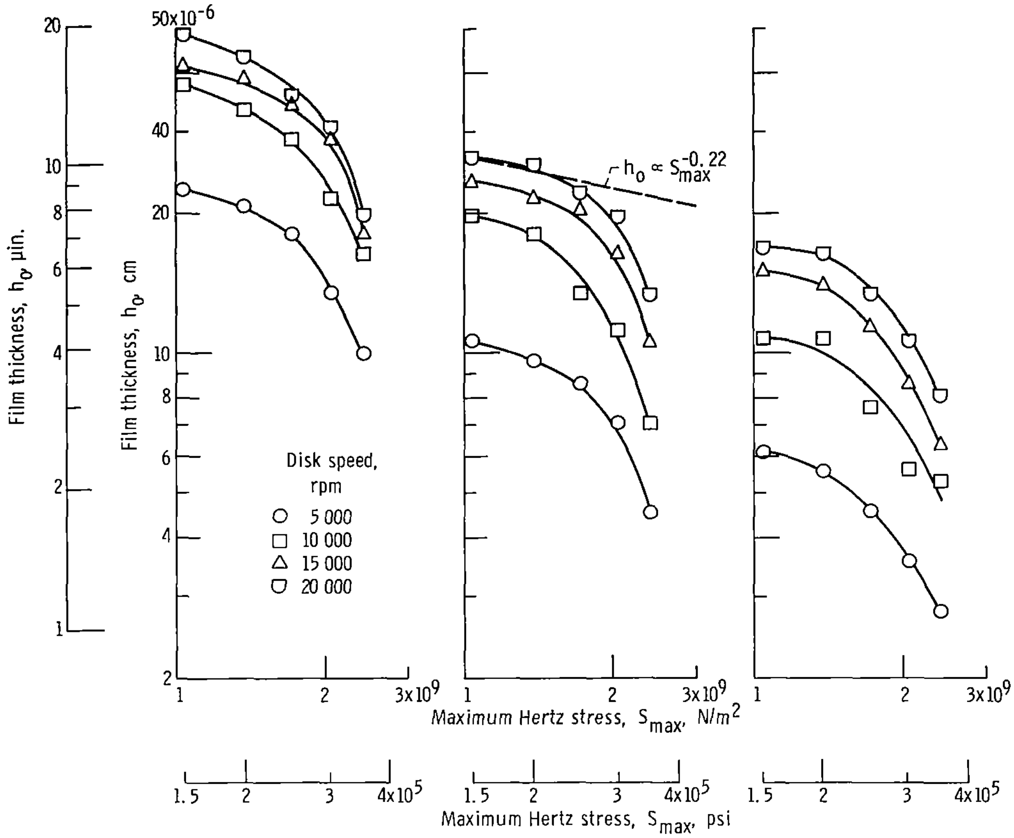


Figure 6. - Experimental film thickness at 1.38×10^9 newtons per square meter (200 000 psi) with the four lubricants tested. All experimental curves lie in band centered at approximately one-half the film thickness predicted by equation (2).

Effect of Stress Level

Measured film thickness between crowned-cone disks is plotted as a function of maximum Hertz stress in figures 7 and 8 for the ester and the fluorocarbon, respectively. Similar data are shown in figure 9 for the polyphenyl ether with crowned disks. It is observed that to about 1.38×10^9 newtons per square meter (200 000 psi), the data for all three lubricants tend to confirm the relation of film thickness to stress predicted by equation (2), where $h_o \propto S_{max}^{-0.22}$. At stresses above 1.38×10^9 newtons per square



(a) Disk temperature, 339 K (150° F).
(b) Disk temperature, 366 K (200° F).
(c) Disk temperature, 422 K (300° F).

Figure 7. - Effect of maximum Hertz stress on measured film thickness with type II ester. Crowned-cone disks.

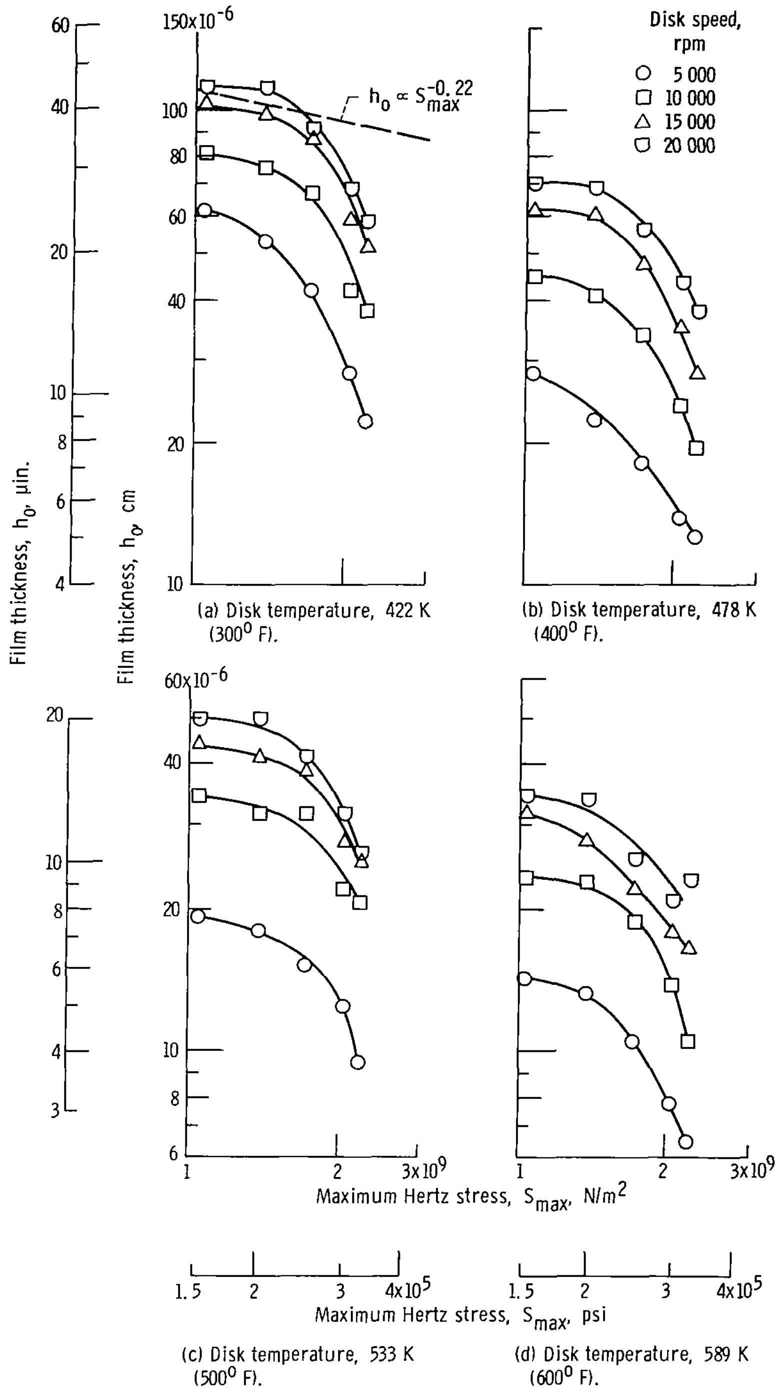


Figure 8. - Effect of maximum Hertz stress on measured minimum film thickness with the fluorocarbon. Crowned-cone disks.

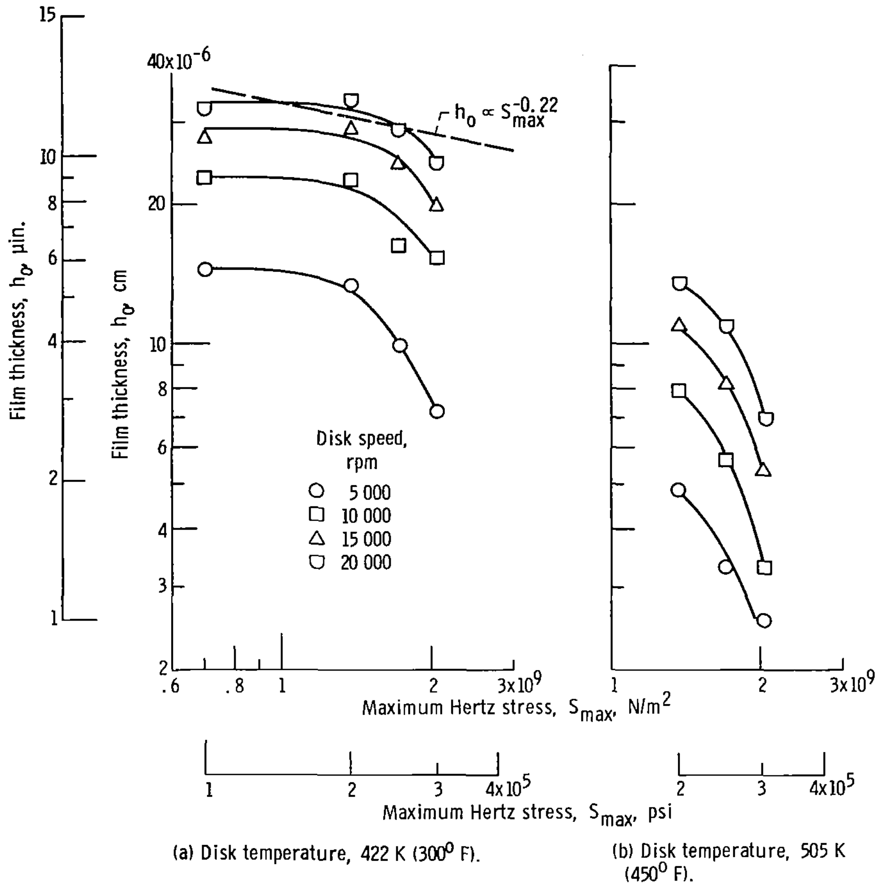


Figure 9. - Effect of maximum Hertz stress on measured minimum film thickness with polyphenyl ether. Crowned disks.

meter (200 000 psi), film thickness decreased at a rate much greater than that predicted by equation (2). This phenomenon is true for all three lubricants as well as for the synthetic paraffinic oil (ref. 11) as shown in figure 10 (p. 18).

The stresses (applied loads) and temperatures in this experimental investigation are considerably higher than in other published data which have shown good correlation with predicted film thickness magnitude (such as refs. 18 and 19).

The present film thickness data correlated well with data in reference 20, which show film thicknesses measured by an X-ray technique to be consistently smaller than predicted. The theory used for comparison was that of reference 15 and is for line contact. The contact between the disks used in reference 20 more closely simulated line contact than does that used in the present investigation. Although the highest maximum Hertz stress reported in reference 20 was only about 1.24×10^9 newtons per square meter (180 000 psi), a greater-than-predicted effect of stress on film thickness was also apparent.

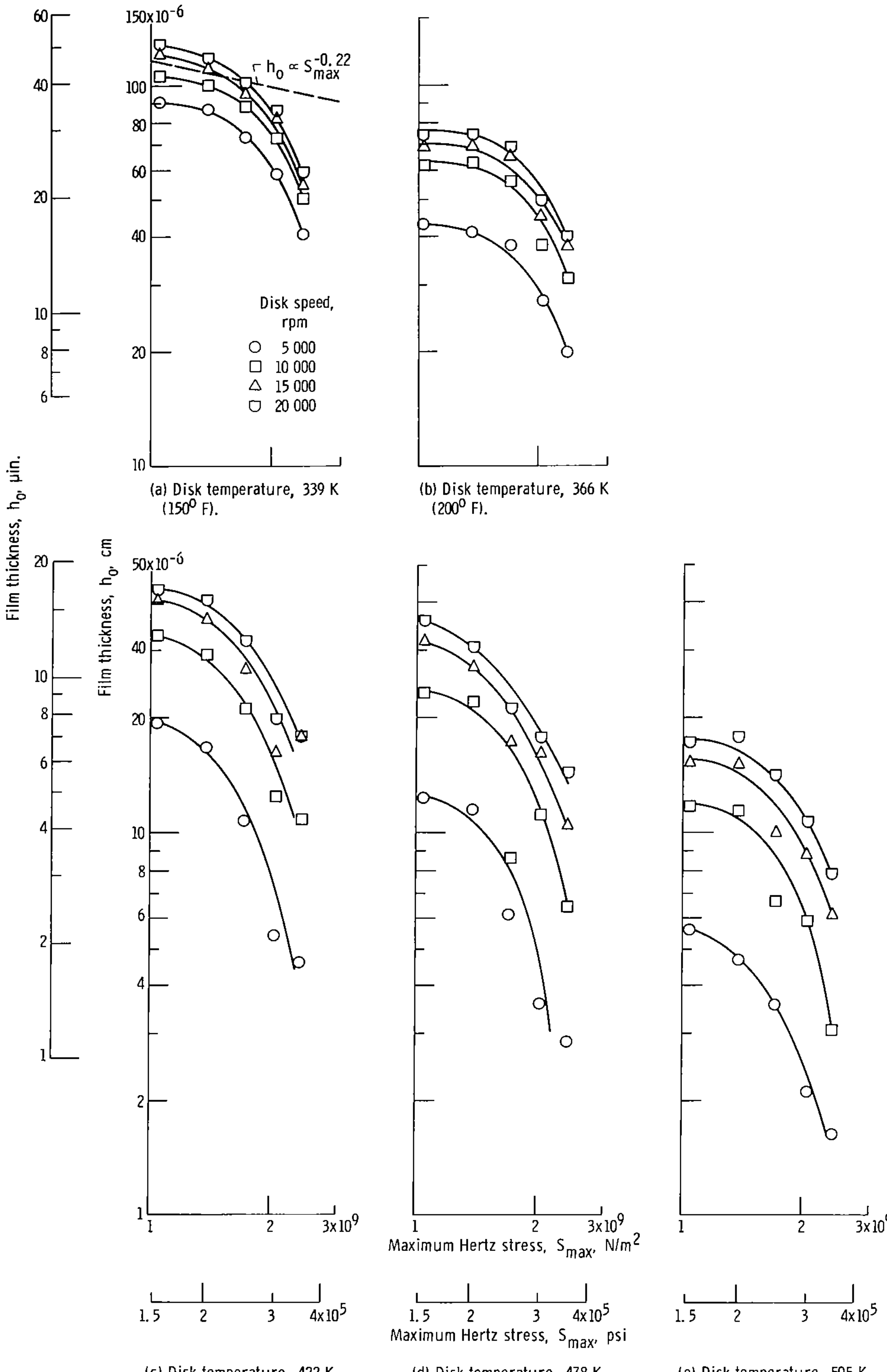


Figure 10. - Effect of maximum Hertz stress on measured minimum film thickness with paraffinic oil. Crowned-cone disks. (Data from ref. 11.)

It has been shown theoretically (ref. 1) that the minimum film thickness in an elastohydrodynamic contact occurs in the exit region. Experimental results (ref. 21) show that the film is thinner at the sides than at the exit or in the center of the contact. It is expected that the X-ray transmission technique measurement is indicative of the minimum film at the exit rather than an average or center film thickness. The difference between the exit and the center film thickness is, however, probably of the order of 10 to 20 percent (ref. 21). This difference would account for only a small portion of the deviation between the predicted and experimental film thicknesses of this investigation. It may, however, be significant in the lower film thickness range, that is, less than 25×10^{-6} centimeter (10 μin.). It has also been shown (ref. 21) that this minimum film thickness varies more with applied stress than does the center film thickness.

When the separation of two rolling disks approaches the height of the surface asperities, the effect of these asperities on X-ray transmission must be considered. The disks used in these tests had surface finishes of 2.5×10^{-6} to 5.0×10^{-6} centimeter (1 to 2 μin.) rms. This means that surface irregularities may have peak-to-peak heights of as much as 25×10^{-6} centimeter (10 μin.). Thus, when the films measured by the X-ray technique are of the order of a few microinches, the probability that some asperity contact is occurring is great. Some X-ray passage between asperities must occur. It is expected that the film thickness reflected by the X-ray transmission technique represents a separation between some average surfaces between the peaks and valleys of each disk surface. Thus, the measured film thickness must be somewhat greater than the minimum distance between asperity peaks.

The behavior of the pressure coefficient of viscosity α at high stress and temperatures is not well understood. However, there is considerable evidence that the effect of pressure on viscosity cannot be described by a single pressure-viscosity coefficient when shear effects are present (ref. 22). Lower pressure-viscosity coefficients at higher temperatures have also been observed (ref. 18). Finally, there is evidence (refs. 23 and 24) that, in high-speed rolling contact, lubricant viscosity may not increase appreciably with pressure due to a time relaxation effect. In the limiting (ultra-high-speed) case where viscosity does not rise at all with pressure, film thickness is reduced essentially by a factor (refs. 23 and 24) of

$$\frac{2.4}{\alpha(S_{max})^{8/11}}$$

If for example the contact pressure is of the order of 2.07×10^{9} newtons per square meter (300 000 psi), the limiting predicted minimum film thickness would thus be reduced by approximately a factor of 4 from that predicted by Grubin's equation. It is apparent, then, that any one of several effects on the lubrication process, not covered by equation (2), can account for the difference between measured film thickness and theoretical predictions.

Comparison with Bearing Test Results

The crowned-cone disks used in these experiments were designed such that their contact area and also their roll and slip velocities simulate the associated conditions of the ball - inner-race contact of the 120-millimeter-bore ball bearings that were fatigue tested and are discussed in references 7 and 8. All bearing test conditions were included in the X-ray film thickness measurements except disk surface speed. A surface speed of approximately 50 meters per second (2000 in./sec) would simulate bearing tangential speeds. The maximum disk surface speed attained was 37.6 meters per second (1480 in./sec).

Bearing tests (ref. 8) with the fluorocarbon oil at 589 K (600° F) and a maximum Hertz stress of 2.23×10^{9} newtons per square meter (323 000 psi) (inner-race - ball contact) resulted in considerable ball wear and surface distress after a few hours. Subsequent bearing tests at 2.04×10^{9} newtons per square meter (295 000 psi) showed some glazing (ref. 25) and superficial pitting, but the lower stress allowed running the bearings to fatigue lives exceeding the AFBMA calculated (catalog) life. These stresses are in the range where the experimental film thickness data show the greatest effect of stress. It is thus conceivable that a rather small decrease in stress could increase film thickness enough to provide satisfactory separation of the bearing surfaces.

Bearing tests (ref. 8) with the polyphenyl ether at 589 K (600° F) and maximum Hertz stresses of 2.23×10^{9} and 2.04×10^{9} newtons per square meter (323 000 and 295 000 psi) resulted in severe ball wear and surface distress. Experimental film thicknesses measured with polyphenyl ether at these conditions were of the order of 2.5×10^{-6} centimeter (1.0 μin.) or less (below the limit of measurement with the X-ray apparatus). It would not be expected that the small decrease in stress would, in this case, get the bearing "out of trouble." Even at the lower stress, the film thickness was too small to provide satisfactory lubrication or separation of the bearing surface. It was necessary to conduct subsequent bearing tests (ref. 8) with the polyphenyl ether in an air environment so that the beneficial oxide films could prevent the gross surface damage.

Unpublished data from tests with 120-millimeter-bore ball bearings identical to those reported in reference 8 except with the advanced type II ester at 491 K (425° F) and a maximum Hertz stress of 2.23×10^{9} newtons per square meter (323 000 psi) show satisfactory operation with this oil under these conditions. X-ray film thickness measurements at conditions simulating these bearing test conditions indicate EHD films only 2.5×10^{-6} to 5×10^{-6} centimeter (1 to 2 μin.) thick. Based on these data, satisfactory bearing operation would not be expected. It is probably then that the additives play a significant role in the success of this lubricant.

As reported in reference 11, there is good correlation between X-ray film thickness measurements and tests with 120- and 25-millimeter-bore ball bearings with the synthetic paraffinic oil. Tests were run both with and without an antiwear additive in the oil. Very low film thicknesses were measured at conditions similar to those where the bearings suffered surface damage.

In general, the X-ray film-thickness-measuring technique has shown good correlation with full-scale bearing tests based on the data presented herein and in reference 11. In most cases, where film thickness measured with the X-ray rolling-disk machine was low, of the order of a few microinches, trouble was encountered in the bearing tests. These X-ray film thickness measurements have been made at conditions that more closely simulate advanced-turbine-engine thrust bearings (i. e., higher temperature, higher stress, relative spinning in the contact) than have been accomplished in the past. This technique appears to be well suited for advanced screening of lubricants for such high-temperature, high-load applications.

SUMMARY OF RESULTS

Elastohydrodynamic (EHD) film thickness measurements were made in an X-ray rolling-disk machine with three lubricants: an advanced ester, a fluorocarbon, and a polyphenyl ether. The results were compared to those previously obtained with a synthetic paraffinic oil. Disk temperature was varied from 339 to 589 K (150° to 600° F). Load was varied such that the calculated maximum Hertz stress ranged from 0.69×10^9 to 2.42×10^9 newtons per square meter (100 000 to 350 000 psi). Shaft speeds of 5000 to 20 000 rpm gave surface speeds from 9.4 to 37.6 meters per second (370 to 1480 in./sec). Crowned disks both with and without a 10° cone angle were used. The results of these measurements were as follows:

1. Measured film thicknesses were less than predicted by EHD theory for all four lubricants. The measured values generally were one-half to one-third of the theoretical predictions.

2. The variation of measured film thickness with the speed-viscosity parameter $(\mu_0 \alpha u/R_x')^{0.74}$ was similar to that predicted by EHD theory, where μ_0 is ambient viscosity, α is the pressure-viscosity coefficient, u is one-half the sum of the surface velocities of elements 1 and 2, and $R_x' = \left[(1/R_1) + (1/R_2)\right]^{-1}$ where R_1 and R_2 are the radii of elements 1 and 2 in the rolling direction.

3. For a given value of $(\mu_0 \alpha u/R_x')^{0.74}$, the fluorocarbon gave the thickest measured EHD films. The other three lubricants gave generally similar results, all less than those for the fluorocarbon.

4. At maximum Hertz stresses about 1.38×10^9 newtons per square meter (200 000 psi), the measured film thickness decreased at rates much greater than that predicted by EHD theory, where $h_o \propto S_{max}^{-0.22}$ (where h_o is minimum film thickness and S_{max} is maximum Hertz stress). This trend was true for all four lubricants under all conditions of speed and temperature.

5. The X-ray film thickness measurements correlated well with results of 120- and 25-millimeter-bore ball bearing tests with the same lubricants. In general, at conditions of load and temperature where low film thicknesses were measured in the X-ray machine, of the order of a few microinches, significant surface damage was encountered in the bearing tests.

Lewis Research Center,
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