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Density Scaling of the Thermal Conductivity of a Jet Oil

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The application of the new quantitative elastohydrodynamics, which employs real properties of the liquid lubricant, to practical tribology problems obviously requires property measurements at high pressure to parameterize the correlations. The thermal conductivity under elevated pressure has been shown to be essential for nonisothermal situations. A new transient hot-wire instrument for pressure to 600 MPa is described and validated. New measurements are presented of the temperature- and pressure-dependent thermal conductivity of a synthetic oil for jet aircraft engines. The density scaling law, $k = k_0 (\rho/\rho_0)^s$, with exponent approximately equal to the standard value of 3 gives an excellent accounting of the results. The temperature dependence of the conductivity may be ignored in elastohydrodynamic lubrication (EHL) simulations without great loss of accuracy and it may be sufficient to describe the pressure dependence with a general expression, $k = k_0 (\rho/\rho_0)^3$.

KEY WORDS

High Pressure; Thermal Properties; Liquid Lubricants; Elastohydrodynamics

INTRODUCTION

A new approach to numerical modeling of the elastohydrodynamic lubrication (EHL) problem, employing measured viscosity, has resulted in new understanding not possible 10 years ago. Use of a realistic description of the temperature, pressure, and shear dependence of viscosity has led to the first complete prediction (Liu, et al. (1)) of both film thickness and friction under isothermal conditions. Film thickness has been calculated for the rheology of a mixture (Liu, et al. (2); Habchi, et al. (3)) and the effects of shear thinning on scale (Krupka, et al. (4)) and load (Krupka, et al. (5)) dependence of the film thickness have been discovered. Realistic thermal modeling of the lubricated contact response to high sliding speed is more challenging and came a few years later (Habchi, et al. (6), (7); Björling, et al. (8)). These last accomplishments required thermal properties of the liquid at high pressures, which were provided by Ove Andersson at Umeå

University using the transient hot-wire technique (Hakansson, et al. (9)).

Perhaps the first high-pressure measurements of the thermal properties of lubricants was reported by Richmond and coworkers in 1984 (Richmond, et al. (10)). However, it was not until Larsson and Andersson (11) published their measurements and empirical relations for thermal conductivity and heat capacity in 2000 that EHL modeling took advantage of the capability. Kazama (12) used the Larsson and Andersson (11) property relations to model the complete EHL problem. He found that the heat capacity dependence on temperature and pressure had little significance on the film temperature and the contact friction. In contrast, the pressure dependence of the thermal conductivity did significantly affect temperature and friction, so much that the friction was reduced 20% by the neglect of the pressure dependence of thermal conductivity. These results were, however, clouded by the neglect of the shear dependence of viscosity, whose absence would enhance the thermal feedback and by the use of the Roelands correlation for viscosity, which, at high pressure, understates the temperature dependence of the viscosity and would mitigate the thermal feedback.

The new more realistic simulations (Habchi, et al. (6), (7); Björling, et al. (8)), using viscosity measured in viscometers, clearly show that the pressure dependence of the thermal conductivity, k , substantially changes the friction. The increase in k with pressure increases the friction. All other things being equal, a lower conductivity liquid will have lower friction at high sliding speed. Reducing the conductivity reduces the transfer of heat to the rollers, resulting in greater film temperature. The viscosity is reduced by the increased temperature, causing a reduction in shear stress transferred across the film.

The measurement of thermal conductivity in liquids is one of the most challenging property measurements, even under ambient pressure. The heat transfer must be almost entirely conductive; convection and radiation are made negligible. Early measurements of the thermal conductivity of liquids employed a steady-state process between parallel plates or concentric cylinders. The time required to attain steady state provided sufficient time for significant convection driven motion to develop in the gap. Nieto de Castro, et al. (13) point out that the measured thermal conductivity of the standard reference material, toluene, steadily decreased from 1920 to 1980 by about 10% as the contributions of convection and radiation were reduced. Today, the transient hot-wire technique is preferred because there is

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NOMENCLATURE

a	= Thermal diffusivity (m^2/s)
a_V	= Thermal expansivity defined for volume linear with temperature ($^\circ\text{C}^{-1}$)
g	= Isothermal volume coefficient of thermal conductivity
K_0	= Isothermal bulk modulus at $p = 0$ (Pa)
K'_0	= Pressure rate of change of isothermal bulk modulus at $p = 0$
K_{00}	= K_0 at zero absolute temperature (Pa)
k	= Liquid thermal conductivity ($\text{W}/\text{m}\cdot\text{K}$)
k_0	= Thermal conductivity at ambient pressure ($\text{W}/\text{m}\cdot\text{K}$)
p	= Pressure (Pa)

q	= Heat rate per length (W/m)
r	= Wire radius (m)
T	= Temperature (K)
T_R	= Reference temperature (K)
V	= Volume at T and p (m^3)
V_R	= Volume at reference state $T_R, p = 0$ (m^3)
V_0	= Volume at $p = 0$ (m^3)
β_K	= Temperature coefficient of K_0 (K^{-1})
ρ	= Mass density (kg/m^3)
ρ_R	= Mass density at reference state, $T_R, p = 0$ (kg/m^3)
ρ_0	= Mass density at $p = 0$ (kg/m^3)

insufficient time for significant velocity to develop; therefore, convection is eliminated as a source of error.

For organic liquids, thermal conductivity, k , decreases very slowly with temperature and increases rapidly with pressure for the temperature and pressure range of EHL. An interesting feature of the pressure dependence is that the density dependence of k is nearly independent of temperature along any isotherm (Ross, et al. (14)). A parameter, g , the isothermal volume coefficient of thermal conductivity, has been defined as a characteristic property of a liquid (Ross, et al. (14)).

$$g = \left[\frac{\partial \ln k}{\partial \ln \rho} \right]_T. \quad [1]$$

For water, $g \approx 2$, and for low-molecular-mass organic liquids, $2.79 \leq g \leq 3.08$ (Ross, et al. (14)). This means that, for an isotherm,

$$k(T, p) = k_0(T) \left(\frac{\rho(T, p)}{\rho_0(T)} \right)^g = k_0(T) \left(\frac{V(T, p)}{V_0(T)} \right)^{-g}. \quad [2]$$

Here $k_0(T)$ is the ambient pressure conductivity and $V_0(T)$ is the volume at ambient pressure. Because the compressibility of liquids increases rapidly with temperature and k_0 decreases slowly with temperature, conductivity isotherms cross at a pressure, p_0 , for which the conductivity is independent of pressure. In the case of n-heptane, $p_0 \approx 500$ MPa (Menashe and Wakeham (15)). The data of Larsson and Andersson (11) generally place $p_0 < 200$ MPa. For $p > p_0$, the trend reverses and conductivity will slowly increase with increasing temperature. For this reason, the temperature dependence may be ignored in EHL simulations without significant loss of accuracy.

Further complicating thermal modeling of EHL is the anisotropy, which causes shear-dependent viscosity and normal stress effects in lubricants sheared at high shear stress. The alignment and stretching of molecules enhances the conductivity in the shear direction and diminishes the conductivity in the cross-film direction (Wapperom and Hulslen (16)). It is doubtful that this effect will ever be incorporated properly in a simulation or measured under non-Newtonian shear in a lubricant and will not be addressed here.

In this article, a new transient hot-wire instrument is described. The novelty of the present instrument lies in having direct measurement of the sample pressure rather than inferring the pressure from the force on the pressure-generating piston. The first measurements are reported for the temperature and pres-

sure dependence of the relative volume, $V/V_R(T, p)$, and of the thermal conductivity, $k(T, p)$, of a jet engine lubricant, L23699, which is used in high-sliding-speed contacts. The density scaling rule, Eq. [2], is applied to the data.

THE NEW HOT-WIRE INSTRUMENT

Because the thermal conductivity is required at elevated pressures, the instrument must be contained in a thick-walled pressure vessel. The pressure vessel and an intensifier for generating pressure up to 700 MPa are shown in Fig. 1. A commercial pressure transducer (700 MPa \pm 0.2% full scale) is also shown. A heating tape surrounds the vessel and a thermocouple can be seen extending upward out of it. The thermocouple junction resides in a well that is 3 mm from the vessel bore. The vessel plug shown in Fig. 1 houses dual electrical feedthroughs of the mineral-insulated swaged cable type. The pressurizing medium is a low-viscosity polyalphaolefin because the usual diester medium is not compatible with the insulation surrounding the various lead wires. The instrument was pressure tested to 600 MPa. The compressibility of some liquids, however, limits the pressure to lower values.

The hot wire can be seen through a window in a thin, hollow cylindrical guard in Fig. 1. The wire is 22- μm -diameter nickel (Goodfellow Cambridge Limited, 99.6%) concentrically held in the guard with 5- to 7-N tension by a coil spring inside of the black acetal plastic housing shown in Fig. 2. Nickel has a high

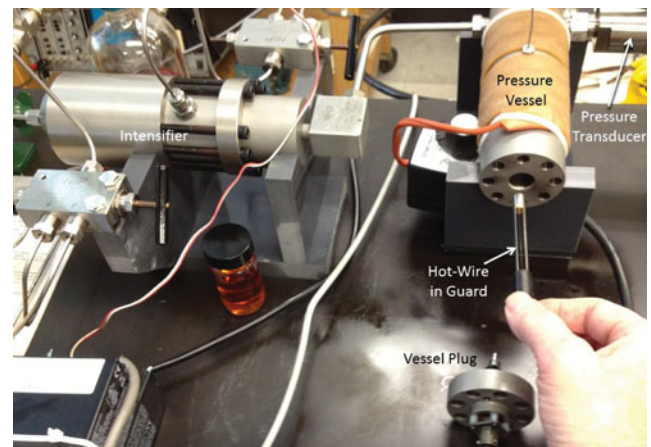


Fig. 1—Transient hot-wire apparatus showing major components.



Fig. 2—Hot-wire probe to be inserted into the volume compensation can.

temperature coefficient of resistivity (0.0068 K^{-1}), ensuring that the temperature of the wire may be accurately determined from the resistance. The length of the wire is 50 mm, giving an electrical resistance of about 10Ω .

Volume compensation is required because the pressurizing medium is separate from the measurement sample. Having a separate liquid to generate pressure allows for the direct measurement of pressure in samples that will become too viscous for hydrostaticity. Changes in sample volume are accommodated by a metal can that encloses the hot wire and guard and may slide over the housing, being sealed by an O-ring shown in Fig. 2. The can is removed from the wire guard in Fig. 2. In operation, the guard is inserted into the can until the O-ring seal is engaged. The greatest volume compression that can be accommodated is 15%, which represents the difference in the internal length of the can and the distance from the seal to the distal end of the guard in Fig. 2. A fill plug is threaded into the closed end of the can after removing air and injecting sample. The pressure difference required to move the seal is less than 0.1 MPa.

The hot wire forms one arm of a Wheatstone bridge. The other three resistances have nearly zero temperature coefficient

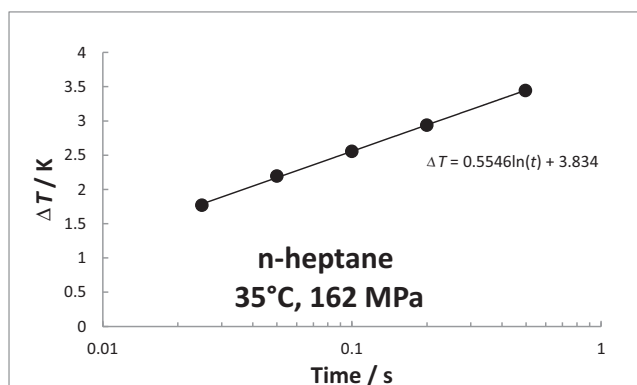


Fig. 3—Time dependence of the temperature of the wire in heptane at elevated pressure.

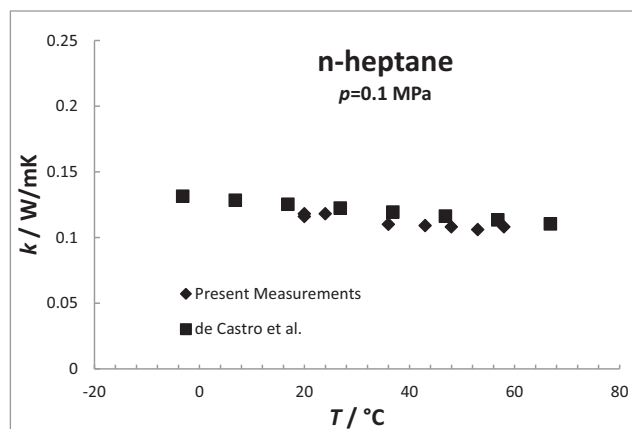


Fig. 4—Validation of the present technique for temperature dependence with the data of Nieto de Castro, et al. (13).

and are adjusted to match the resistance of the hot wire at ambient temperature. For a measurement of $k(T, p)$, the bridge is excited by 1.515 V for a period of 0.5 s. For calibration of the bridge output versus wire temperature, a lower excitation of 0.394 V is employed to reduce the temperature increase during the measurement. Bridge output voltage is readily converted to wire temperature. The current flow in the wire during the 0.5-s pulse of the higher voltage results in a steady increase of the bridge output as the wire temperature rises. The wire temperature is recorded at 25, 50, 100, 200, and 500 ms.

PRINCIPLE OF OPERATION

During the 0.5-s pulse of electrical current, the temperature of the wire, after a very short time, increases in a linear fashion with the logarithm of time, as shown in Fig. 3. Carslaw and Jaeger (17) found an analytical solution for a long cylinder made of a perfect conductor of heat bounded by an infinite medium with thermal diffusivity, a , and conductivity, k . Heat is generated within the cylinder of radius, r , at a heating rate per unit length (W/m) of q for time, $t \geq 0$. There is no heat generation for $t < 0$. The

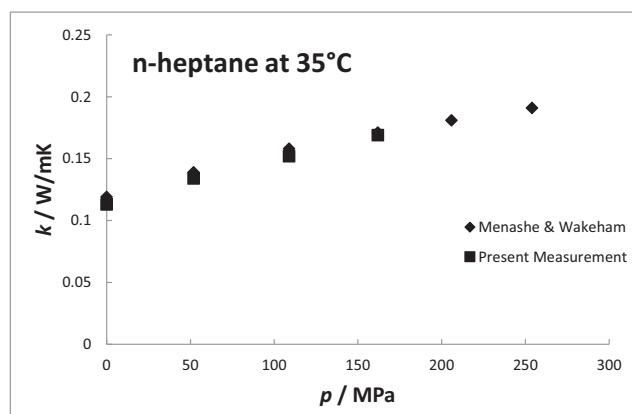


Fig. 5—Validation of the present technique for pressure dependence with the data of Menashe and Wakeham (15).

TABLE 1—THERMAL CONDUCTIVITY OF THE JET OIL IN W/MK

p (MPa)	25°C	75°C
0	0.139	—
50	0.150	0.140
100	0.160	0.153
200	0.179	0.172
300	0.191	0.186

temperature increase is given by

$$\Delta T = \frac{q}{4\pi k} \ln\left(\frac{4at}{1.7811 \cdot r^2}\right). \quad [3]$$

There are additional terms on the right-hand side of Eq. [3] that vanish (Kashiwage, et al. (18)) for large values of the Fourier number, $Fo = \frac{at}{r^2} > 10$. The time dependence of the temperature of the wire in heptane at elevated pressure is shown in Fig. 3. The Fourier number at the first data point at $t = 0.025$ s is approximately 15 to 20. In Fig. 3 it can be seen that the temperature rise can be expressed as $\Delta T = y_0 + m \ln(t)$. Therefore, the thermal conductivity is obtained from the slope of the line, $m = 0.5546$ K, in Fig. 3 as $k = q/4\pi m$.

It is very important that the heating power be calculated using the wire resistance at the nominal temperature of the measurement. Adjusting the power calculation for the resistance increase due to the small temperature rise resulting from the measurement has no significant effect. Inspection of Eq. [3] shows that, in theory, the thermal diffusivity, a , may be obtained with this instrument from the value of y_0 . However, for an accurate determination of y_0 , the start of the electrical pulse must be resolved to about 0.1 ms and this is not possible with the current recording system which captures 1,000 samples over 0.5 s.

The thermal conductivity determination is a direct measurement, not requiring calibration of an unknown parameter. However, it seems to be more challenging than a measurement under high pressure of some other properties such as, for example, viscosity or volume. The wire, for example, is extremely fragile, whereas, at high pressure, liquid motion can generate very large forces on internal structures.

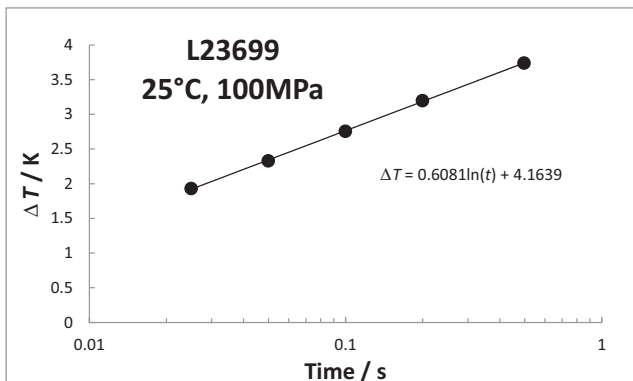


Fig. 6—Time dependence of the temperature of the wire in jet oil at elevated pressure.

TABLE 2—THE RELATIVE VOLUME, V/V_R , OF THE JET OIL

p (MPa)	25°C	60°C	100°C
0	1.0000	1.0238	1.0580
10	0.9948	1.0180	1.0490
50	0.9741	0.9954	1.0189
100	0.9539	0.9707	0.9908
200	0.9244	0.9372	0.9530
300	0.9024	0.9140	0.9266
400	0.8854	0.8954	0.9060

VALIDATION

Water and toluene have become standard reference liquids for thermal conductivity. These were proposed by Nieto de Castro, et al. (13) as primary standards because the confidence limits on published values are around 1%. Unfortunately, the conductivity of water is many times greater than lubricants and, though toluene has similar values, it is not compatible with the same seal materials that are compatible with lubricants.

Nieto de Castro, et al. (13) also proposed n-hexane as a secondary standard with wider confidence limits. Here, their published data are employed to validate the technique at ambient pressure for the temperature dependence using the comparison in Fig. 4. The present measurements are 3 to 7% lower than the values reported by Nieto de Castro, et al. (13). The pressure dependence can be validated by the comparison with the elevated pressure data of Menashe and Wakeham (15) for n-hexane. These are compared in Fig. 5 at a temperature of 35°C for pressure to 162 MPa. The present measurements are 1 to 3% lower than the published values.

For the first attempt at validation, pressures to 260 MPa were employed; however, the relative volume of n-hexane is $V/V_0 = 0.83$ at this pressure if V_0 is the ambient pressure volume. This exceeded the maximum available volume compression and resulted in crushing of the guard. Hexane is extremely compressible in comparison to most lubricants. For example, the jet oil will reach the same relative volume at about 800 MPa. New structural components were fabricated to complete the validation.

It is difficult to explain the present data being consistently slightly lower than the reference data. The usual sources of error, convection and radiation, will increase the measured conductivity. This deviation from reference data could be accommodated by a 3% increase in the reported thermal conductivities. In any event, such an increase will not noticeably affect the prediction of friction in EHL and it is remotely possible that these measurements actually represent improved accuracy.

TABLE 3—PARAMETERS OF THE TAIT EQUATION FOR THE JET OIL

K'_0	10.826
K_{00} (GPa)	8.797
β_K (K^{-1})	0.00566
a_V ($^{\circ}C^{-1}$)	0.000765
SD	0.09%

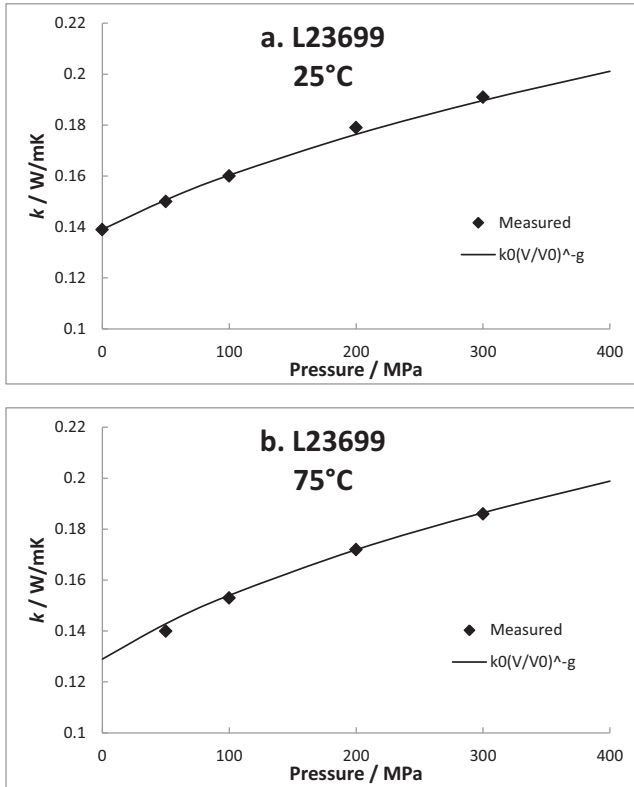


Fig. 7—Density scaling law, Eq. [2], applied to the measured conductivities.

MEASUREMENTS OF THE JET OIL

A jet oil meeting specification L23699 is Mobil Jet II. The sample was obtained commercially. The viscosity of this oil has been measured and modeled at pressures to 1.4 GPa and temperatures to 220°C (Bair (19)). The measured thermal conductivities are listed in Table 1. A representative heating curve is shown in Fig. 6. The ambient pressure measurement is missing at 75°C. The temperature was increased from 25°C only under elevated pressure.

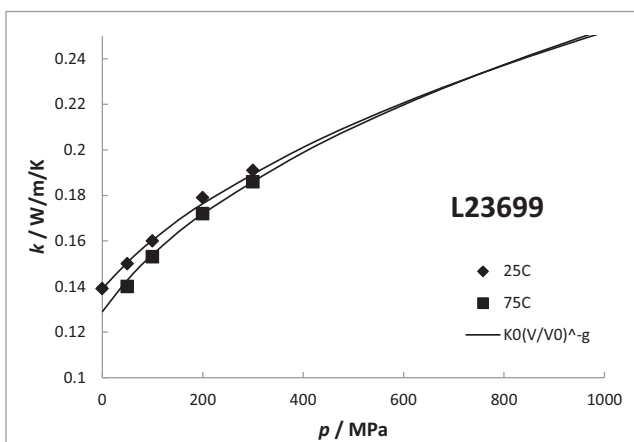


Fig. 8—Thermal conductivities extrapolated to high pressure with the scaling law, Eq. [2], to show crossing of isotherms.

The volume compensation can be installed with the seal just to the point of engagement. This was done conservatively to avoid crushing the structure at the highest pressure; however, this positioning did not allow for thermal expansion at ambient pressure.

To apply density scaling will require an equation of state. The relative volume was measured as a function of temperature and pressure in a metal bellows piezometer. This instrument has been described previously (Bair (19)). A metal bellows containing the sample is placed inside of a pressure vessel. The length of the bellows is measured at various pressures and temperatures. The resulting volumes, relative to the volume, V_R , at a reference state of 25°C and ambient pressure are listed in Table 2.

DENSITY SCALING

The Tait equation of state is used here.

$$\frac{V}{V_0} = 1 - \frac{1}{1 + K'_0} \ln \left[1 + \frac{p}{K_0} (1 + K'_0) \right], \quad K_0 = K_{00} \exp(-\beta_K T),$$

$$\frac{V_0}{V_R} = 1 + a_V (T - T_R). \quad [4]$$

Fitting this equation to the data in Table 2 resulted in the parameters listed in Table 3. $T_R = 25^\circ\text{C}$.

The density scaling law, Eq. [2], $k = k_0 (V/V_0)^{-g}$, with V/V_0 calculated from Eq. [4], was fitted to the measured conductivities in Table 1. The parameters were determined to be $k_0(25^\circ\text{C}) = 0.139$, $k_0(75^\circ\text{C}) = 0.129$ W/mK, and $g = 3.02$ with a standard deviation of 1.1%. For comparison, Ene (20) reported for an L23699 oil (not necessarily the same) that at ambient pressure the thermal conductivity at 25 and 75°C is 0.135 and 0.129 W/mK, respectively. The resulting fit to the data is shown in Figs. 7a and 7b. In Fig. 8 it can be seen that extrapolation leads to $p_0 \approx 600$ MPa, which is not an unusual pressure for the hertz region of EHL. If great accuracy is not required, it should be sufficient to model the thermal conductivity as $k = k_0 (\rho/\rho_0)^3$, which is convenient because, in any event, an accurate expression for $\rho(T, p)$ is required for a compressible simulation. It should be obvious that the Dowson and Higginson equation of state, used in classical EHL, will not be useful for thermal conductivity scaling because, in that case, the compressibility is assumed to be independent of the material and the temperature and, also, there is a limit to the volume compression.

CONCLUSIONS

1. The application of the new quantitative elastohydrodynamics, which employs real properties of the liquid lubricant, to practical nonisothermal problems presently requires measurements of thermal conductivity of the lubricant at elevated pressure to parameterize any correlation of the property with temperature and pressure.
2. A new transient hot-wire instrument for pressure to 600 MPa is described and validated with a reference liquid.
3. New values for the thermal conductivity, k , of a jet oil are reported.
4. A simple density scaling law, $k = k_0 (\rho/\rho_0)^g$, describes the measured conductivity.
5. The temperature dependence may be ignored in EHL simulations without great loss of accuracy and it may be sufficient to

describe the pressure dependence with a general expression,
 $k = k_0 (\rho/\rho_0)^3$.

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