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Lubricant thermal conductivity and heat capacity under high pressure

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Abstract: The thermal conductivity λ and the heat capacity per unit volume, ρc_p , have been measured for a number of common lubricating oils. The oils tested were paraffinic and naphthenic mineral oils and a 50/50 blend of these. Poly- α -olefin, polyglycol, Santotrac, ester and rapeseed oils have also been tested. The measurements, using the **transient hot-wire method**, were carried out under isothermal conditions over **a pressure range from atmospheric to 1.1 GPa** and at two temperatures, 295 and 380 K (**22 and 107 °C** respectively).

The temperature had only a marginal effect on thermal conductivity; however, the thermal conductivity was doubled as the pressure was increased to 1 GPa. The heat capacity per unit volume was influenced by both the pressure and the temperature. Some of the lubricants solidified as the pressure increased and the transition from a fluid to a solid state could be detected in the measurements of ρc_p .

The relationship between the thermodynamic properties and the pressure and temperature are described by two empirical equations. These equations can be used in thermal elastohydrodynamic analyses.

Keywords: thermal conductivity, heat capacity, elastohydrodynamic lubrication, lubricants, high pressure

NOTATION

b_1, b_2	constants in the empirical expression for ρc_p
c_1, c_2	constants in the empirical expression for λ
c_p	heat capacity of the lubricant (J/kg K)
k_1, k_2	constants in the empirical expression for ρc_p
p	pressure (Pa)
p_g	glass transition pressure (Pa)
T	temperature (K)
T_0	reference temperature (K)
β	second-order polynomial in the empirical expression for ρc_p
λ	thermal conductivity of the lubricant (W/m K)
λ_0	thermal conductivity of the lubricant at T_0 and atmospheric pressure (W/m K)
ρ	density of the lubricant (kg/m ³)
$(\rho c_p)_0$	heat capacity per unit volume at T_0 and atmospheric pressure (J/K m ³)

1 INTRODUCTION

The understanding of elastohydrodynamic lubrication (EHL) requires knowledge about lubricant properties. To be applicable to EHL, these properties have to be measured under realistic conditions, i.e. at a high pressure and high shear strain rate and over a relatively broad temperature range.

The most important properties are those that affect the lubricant rheological model, i.e. the relationship between the shear stress and the shear strain rate at pressures from atmospheric pressure to 2–3 GPa and at temperatures between -30 °C and up to many hundred of degrees Celsius. Many attempts have been made to obtain such measurements (see, for example, references [1] to [5]) and different methods have been used in order to cover these broad pressure and temperature ranges.

Various models have been developed from the measured relationship between the stress and the strain rate and been applied in numerical simulations of EHL (see, for example, references [6] to [11]). Current models are, however, still not accurate enough to make it possible to simulate EHL under all different operating conditions such as a high rolling speed and/or a high sliding speed. It is still very difficult to estimate the traction and even the film thickness under such conditions. Recent research [11] has shown that rheological models such as those suggested by Eyring and by Bair and Winer lead to unrealistic results.

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While thermal effects also play an important role under conditions with high rolling and/or sliding speeds there are only a few reports in the literature on the solution of the full non-Newtonian thermal EHL problem (see, for example, references [8] to [10]). Taking the thermal effects into account requires knowledge of additional properties. These properties may not be as important as the rheological properties, such as the viscosity and the pressure–viscosity coefficient, but still they have a significant effect on the results.

This paper investigates two of these properties, namely the thermal conductivity and the heat capacity per unit volume. Both properties influence the lubricant temperature and thus, indirectly, the rheology. These have been studied in only a few previous investigations, such as that by Richmond *et al.* [12]. Results from measurements under a high pressure at two different temperatures will be presented for a number of common lubricating oils. The measured relationship between these thermodynamic properties and the pressure and temperature can be used in future thermal EHL analyses and to establish more accurate models of the behaviour of lubricants under EHL conditions. The experimental results also allow the solidification pressure at different temperatures to be determined.

2 EXPERIMENTAL METHOD

The transient hot-wire method [13] was used to measure simultaneously the thermal conductivity λ and the heat capacity per unit volume, ρc_p , at different pressures. The hot-wire probe was a Ni wire (of 0.1 mm diameter) placed horizontally in a ring of constant radius within a Teflon cell. The wire, surrounded by the medium under investigation, was heated by a 1.4 s pulse of approximately constant power and the wire resistance measured against time. From this, the temperature rise of the wire could be determined. A theoretical expression for the temperature rise was fitted to the data points, thereby yielding λ and ρc_p . For temperatures above 100 K, the inaccuracy was estimated as ± 2 per cent for λ and ± 5 per cent for ρc_p .

The Teflon sample cell was mounted in a piston–cylinder type of pressure vessel with an internal diameter of 45 mm and a load was applied using a 5 MN hydraulic press. The temperature was varied by cooling or heating the whole pressure vessel and was measured using an internal chromel versus alumel thermocouple, which had been calibrated against a commercially available (calibrated) silicon diode thermometer. The pressure was determined from the load divided by the area with an empirical correction for friction, which had been established by comparison with directly measured pressure in a hydrostatic experiment. The inaccuracy in temperature measurement was estimated as ± 0.5 K and the inaccuracy in

pressure as ± 40 MPa at 1 GPa. Measurements were made along isotherms.

3 LUBRICANTS AND TEST CONDITIONS

The tested lubricants are listed in Table 1. Lubricants 6 to 8 are fully formulated, commercially available lubricants while the rest of the lubricants are base fluids without any additives. The measurements were carried out under isothermal conditions at two different temperatures: 295 ± 2 K (22 °C) and 380 ± 2 K (107 °C).

4 RESULTS AND DISCUSSION

Figures 1 and 2 show the thermal conductivity λ at 295 and 380 K as the pressure varies from atmospheric pressure to 1.1 GPa. It can be seen that the thermal conductivity doubles as the pressure increases to 1 GPa. Interestingly, the thermal conductivity varies widely between different lubricant types. The lowest values were found for the traction fluid, Santotrac, and the highest values for TMP oleat, rapeseed and PAO. It should be noted that the local maxima that some of the lubricants exhibit corresponds to the transition to a solid (almost certainly glassy) phase. At the glass transition, the hot-wire method used in this investigation yields an anomalous maximum in the thermal conductivity.

While the effect of temperature is relatively small, the thermal conductivity does increase slightly as the temperature increases. A weak temperature dependence is typical for materials with disordered states such as liquid and glassy states. It can be seen that the paraffinic–naphthenic blends have roughly the same thermal conductivity, from which it can be concluded that the molecular size has no significant influence for viscosities in the range from VG32 to VG150. Figures 3 and 4 show the pressure and temperature dependences for the heat capacity per unit volume, ρc_p . Transitions from the fluid to the solid state are clearly seen as an abrupt drop in ρc_p as the pressure increases, which is due to a decrease in c_p . The naphthenic

Table 1 Tested lubricants

Number	Type	Viscosity grade (ISO)
1	Paraffinic mineral	VG150
2	Naphthenic mineral	VG150
3	50% paraffinic + 50% naphthenic mineral	VG32
4	50% paraffinic + 50% naphthenic mineral	VG68
5	50% paraffinic + 50% naphthenic mineral	VG150
6	Poly- α -olefin (PAO)	VG150
7	Polyglycol	VG150
8	Santotrac 50 (traction fluid)	\approx VG22
9	Ester (TMP oleat)	VG46
10	Rapeseed oil	VG32

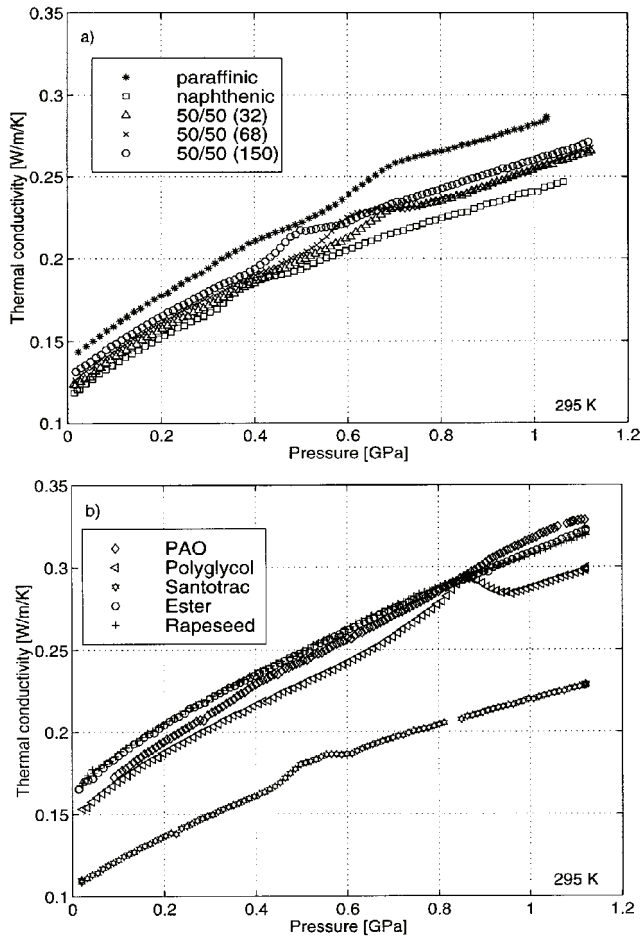


Fig. 1 Thermal conductivity versus pressure at 295 K: (a) lubricants 1 to 5; (b) lubricants 6 to 10

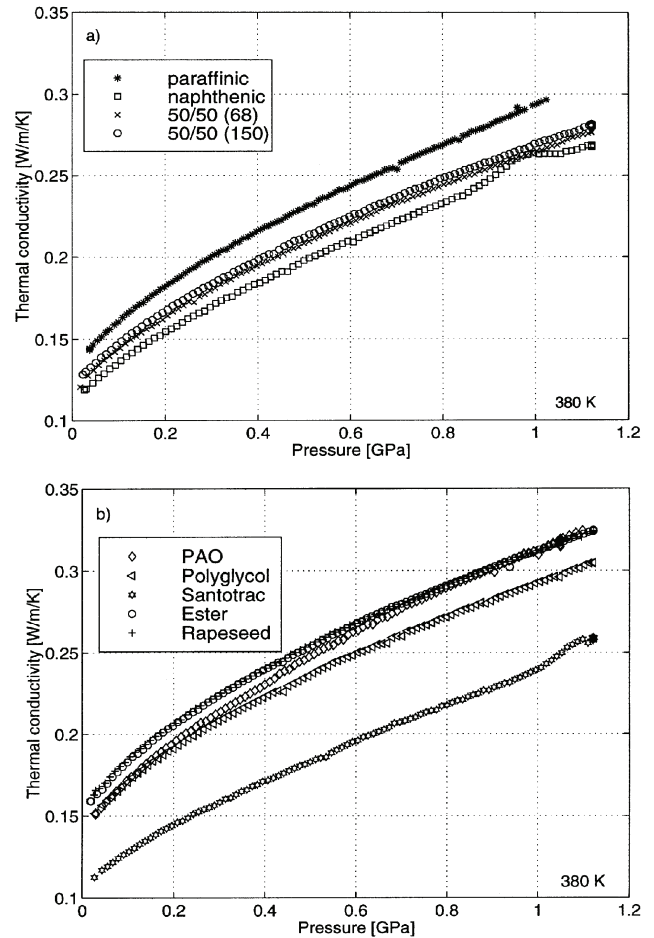


Fig. 2 Thermal conductivity versus pressure at 380 K: (a) lubricants 1, 2, 4 and 5; (b) lubricants 6 to 10

oil shows, for example, a transition at a pressure between 0.32 and 0.6 GPa at 295 K (Fig. 3a). The heat capacity per unit volume increases as the pressure is increased both in the fluid state and in the solid state. This is due to the increase in the density since the heat capacity actually decreases slightly on increasing the pressure.

The solidification pressure is moved to higher values as the temperature is increased. The transition for the naphthenic oil occurs above 0.85 GPa at 380 K (Fig. 4a). An increased temperature also increases ρc_p , i.e. the heat capacity increases with increasing temperature since the density decreases as the temperature is increased.

All three blends of paraffinic and naphthenic oils have the same ρc_p , but the transition regions differ. The more viscous oils have, as expected, a lower solidification pressure.

To enable accurate simulation of the temperatures in EHL contacts, it is necessary to consider the variation in the thermal conductivity with the pressure (and the temperature). This is especially important in the high-pressure region of the contact, i.e. near the contact centre. The temperature distribution in the lubricant film in this region is dominated by the conduction of heat to the

bounding surfaces. This means that the temperature would be overestimated if the values of the thermal conductivity at atmospheric pressure are used. If the temperature cannot be determined accurately, then neither can the traction because the temperature has a strong influence on the lubricant's rheology.

In order to make future simulations more accurate, the following empirical equations for the thermal conductivity λ (W/m K) can be used:

$$\lambda = \lambda_0 \left(1 + \frac{c_1 p}{1 + c_2 p} \right) \quad (1)$$

where p is the pressure (GPa) and the constants λ_0 , c_1 and c_2 for the different lubricants are given in Table 2. As the influence of the temperature is small, equation (1) can be applied without correction at temperatures between 295 and 380 K and pressures between atmospheric pressure and 1.1 GPa.

Convective effects are more pronounced in the inlet of the contact where shear heating and back flow may increase the temperature significantly. In order to determine the inlet temperature it is important to use

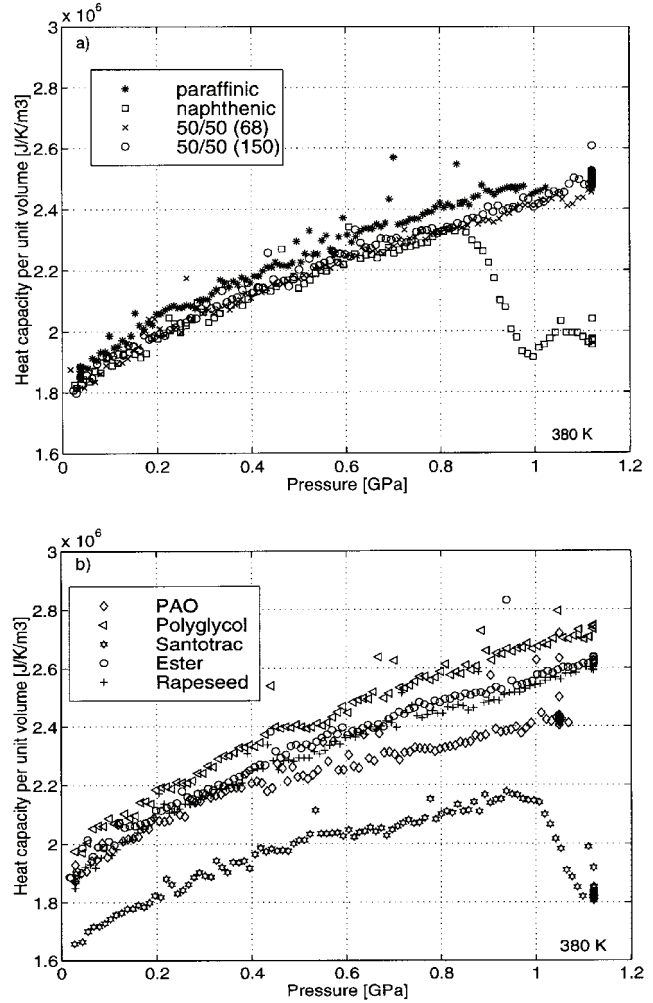
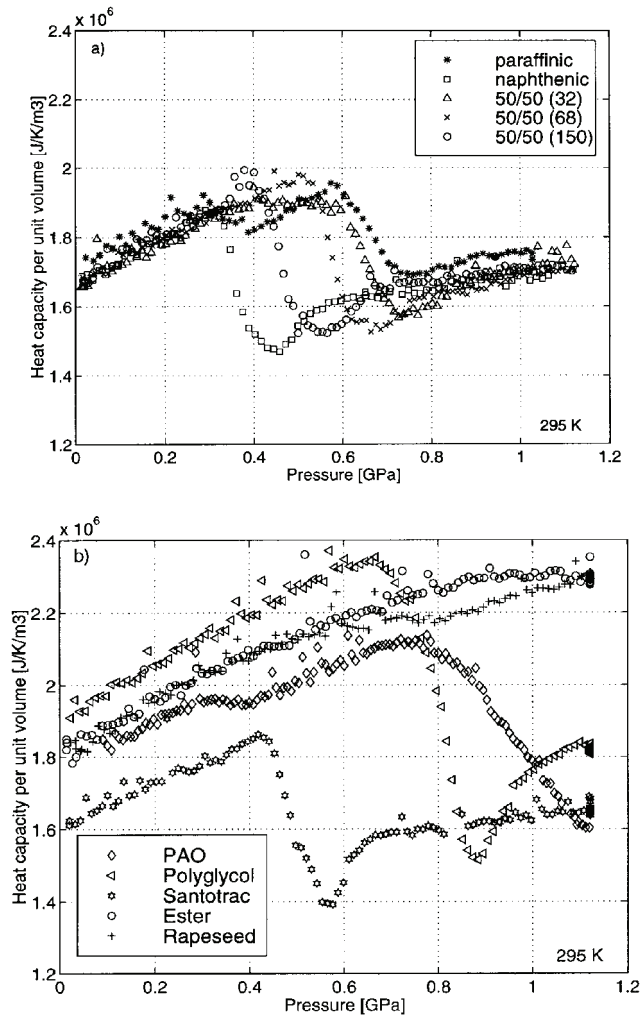


Fig. 3 Heat capacity per unit volume, ρc_p versus pressure at 295 K: (a) lubricants 1 to 5; (b) lubricants 6 to 10

Fig. 4 Heat capacity per unit volume, ρc_p versus pressure at 380 K: (a) lubricants 1, 2, 4 and 5; (b) lubricants 6 to 10

Table 2 Constants in the expression for $\lambda(p)$ [equation (1)] for different lubricants

Lubricant type	λ_0 (W/m K)	c_1	c_2
Paraffinic mineral	0.137	1.72	0.54
Naphthenic mineral	0.118	1.54	0.33
PAO	0.154	1.40	0.34
Polyglycol	0.148	1.56	0.61
Santotrac	0.104	1.85	0.50
Ester (TMP oleat)	0.162	1.44	0.56
Rapeseed oil	0.164	1.41	0.58

accurate values of ρc_p . The lubricant is fluid in the low-pressure inlet region and, in this pressure range, ρc_p (J/K m^3) is well described by

$$\rho c_p = (\rho c_p)_0 [1 + \beta(p)(T - T_0)] \left(1 + \frac{k_1 p}{1 + k_2 p} \right) \quad (2)$$

where T is the temperature (K), p is the pressure (GPa) and the constants $(\rho c_p)_0$, T_0 , k_1 and k_2 are given in Table 3. The parameter $\beta(p)$ is a second-order polynomial:

Table 3 Constants in the expression for $\rho c_p(p, T)$, [equation (2)]

Lubricant type	$10^{-6}(\rho c_p)_0$ (J/K m^3)	k_1	k_2	β_0	b_1	b_2	T_0 (K)
Paraffinic mineral	1.71	0.47	0.81	9.3×10^{-4}	1.4	-0.51	295
Naphthenic mineral	1.64	0.56	0.80	9.9×10^{-4}	0.58	-0.46	295
PAO	1.77	0.41	1.05	6.5×10^{-4}	2.7	-1.5	295
Polyglycol	1.89	0.50	0.51	3.4×10^{-4}	3.3	-2.3	295
Santotrac	1.60	0.48	0.71	4.5×10^{-4}	1.8	-0.10	295
Ester (TMP oleat)	1.81	0.49	0.67	6.1×10^{-4}	1.6	-0.78	295
Rapeseed oil	1.79	0.52	0.73	5.7×10^{-4}	1.3	-0.54	295

$$\beta(p) = \beta_0(1 + b_1 p + b_2 p^2) \quad (3)$$

where β_0 , b_1 and b_2 are also given in Table 3 and the pressure p is in gigapascals. Equations (2) and (3) are valid below the solidification pressure only and over the temperature range 295–380 K.

Alsaad *et al.* [14] used dilatometry in order to measure the solidification pressure. Their isothermal results can be compared with the results obtained from the present investigation (Fig. 5). The transition range for Santotrac 50 from reference [14] is shown as dashed lines in Fig. 5. The transition range for the Santotrac from the present investigation (Figs 3 and 4) are shown as horizontal solid lines in Fig. 5. The agreement between the two different methods is good at 295 K. At 380 K it is difficult to compare but it seems as if the transition occurs at a slightly lower pressure in the hot-wire measurements.

It should be remembered that both the dilatometric and the hot-wire measurements are carried out under nearly static conditions. This is not the case in real EHL contacts where the thermal properties may well be influenced by the loading rate and also the molecule alignment in the direction of shear.

The solidification pressure or glass transition pressure p_g is presented in Table 4. This pressure is defined here as the

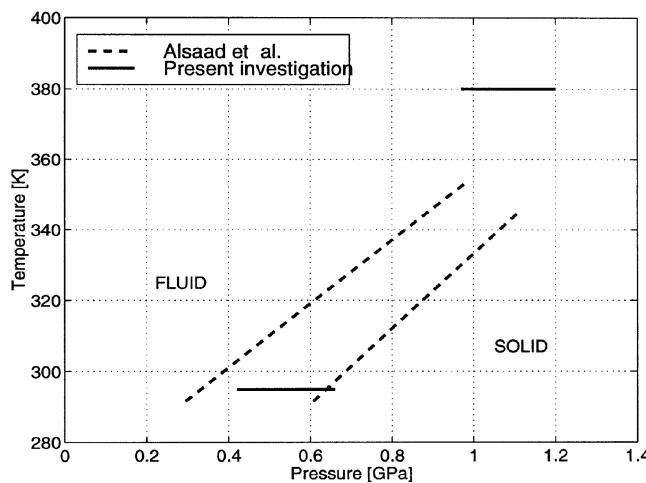


Fig. 5 Transition regions under isothermal conditions: - - -, beginning of the transition and end of the transition for Santotrac 50 presented in reference [14]; —, transition for Santotrac in the present investigation

Table 4 Glass transition pressures at 295 and 380 K

Lubricant type	P_g (GPa)	
	At 295 K	At 380 K
Paraffinic mineral	0.7	>1.0
Naphthenic mineral	0.4	0.95
PAO	≈1.1	>1.1
Polyglycol	0.85	>1.1
Santotrac	0.55	≈1.1
Ester (TMP oleat)	>1.1	>1.1
Rapeseed oil	>1.1	>1.1

pressure where the thermal conductivity exhibits a local maximum and where the heat capacity per unit volume exhibits a local minimum (see Figs 1 to 4). In fact the anomalous maximum and minimum occur at a relaxation time of roughly 1 s, which is the duration of the hot-wire pulse and, therefore, the time scale of the method. The calorimetric glass transition corresponds roughly to a relaxation time of 10^3 s.

5 CONCLUSIONS

The thermal conductivity λ and the heat capacity per unit volume, ρc_p , have been measured under isothermal conditions over a pressure range from atmospheric pressure to 1.1 GPa. The results showed that thermal conductivity doubled as the pressure is increased to 1 GPa and that the lubricant type has a significant influence on the thermal conductivity. For example, a traction fluid, Santotrac, showed a 35 per cent lower thermal conductivity than ester lubricants such as TMP oleat and rapeseed oil. The temperature has only a small effect on the thermal conductivity. It decreases less than five per cent between room temperature and 380 K.

The heat capacity per unit volume is highest for the polyglycol and ester lubricants while Santotrac shows the lowest values. The heat capacity per unit volume increases with increasing pressure, and ρc_p is lower in the solid state than in the fluid state, which is due to a significantly lower c_p .

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