1

The Lubricant

The role of the lubricant in internal combustion engines, and more generally in any lubricated mechanism, is to reduce friction, to evacuate heat and to hold in suspension and carry away the solid or liquid impurities formed during an operation. Reduction in friction is obtained simply by maintaining a lubricant film between the moving surfaces. This prevents them from making contact with each other, and as a result, prevents wear from occurring on the mechanical pieces. It is also very important that the lubricant can effectively evacuate the heat that comes from the friction between the various pieces, which make contact with each other, or from the combustion, while still maintaining its initial properties. Additionally, it is of great importance that the lubricant should remain effective when exposed to water, combustion acids or any other contaminant particles.

Obtaining a lubricant that can fulfill these three fundamental functions is a complex task requiring a compromise between the base oil properties and the influence of the different additives intended to improve the behavior of these base oils.

1.1. Description of lubricants

Depending on their origin, base oils can be classified into two main categories: mineral and synthetic. Mineral oils are obtained from crude oil and may in turn be divided into several groups, depending on the origins of the oil and the refining procedures used.

Synthetic base oils are products obtained artificially, and are superior to mineral base oils, but are also more expensive than them. They perform better thermally, are more stable when faced with oxidation and are less volatile, etc. Some synthetic

base oils may be mixed with mineral oils in order to obtain the required properties for volatility at high temperature and/or viscosity at low temperature.

The most important requirements for a good lubricant are:

– reduced volatility at operating conditions; this property is inherent to the base oil and cannot be improved by additives;

– good flow characteristics at operating temperatures; this property largely depends on the base oil used, but may also be improved by adding dispersant additives and additives which modify viscosity;

– good stability or capability for the lubricant to maintain its characteristics for a long time; even if this property depends to a certain extent on the base oil used, it is mostly controlled by the additives. The stability of the lubricant depends on the environment in which it is used (temperature, potential oxidation, contamination with water, with unburnt combustible, combustion soot or various acids). This is where additives really make a major contribution in the improvement of performance and the lifetime of lubricants;

– compatibility with the system's other materials; this property depends partially on the base oils, but the additives can also have a major influence here.

In internal combustion engines, the performance of a lubricant is judged on its capacity to reduce friction, resist oxidation, minimize the formation of deposits and prevent corrosion and wear. To fulfill all these conditions, the lubricants used for the lubrication of internal combustion engines incorporate several types of additives: antiwear and extreme-pressure agents, antirust agents and corrosion inhibitors, detergents and dispersants, additives lowering the pour point and improving the viscosity index, antifoaming and demusifying/emulsifying agents and antioxidants.

1.2. The viscosity

According to the standard ISO 3104-1994 [ISO 94; NOR 96], "the viscosity of a liquid is the property of the liquid related to the level of resistance with which its molecules oppose a force within it which causes them to slide". Since viscosity determines the loading capacity, lubricant film thickness and losses through friction, knowledge and modeling of its variation in function of different parameters are essential to the study of bearings.
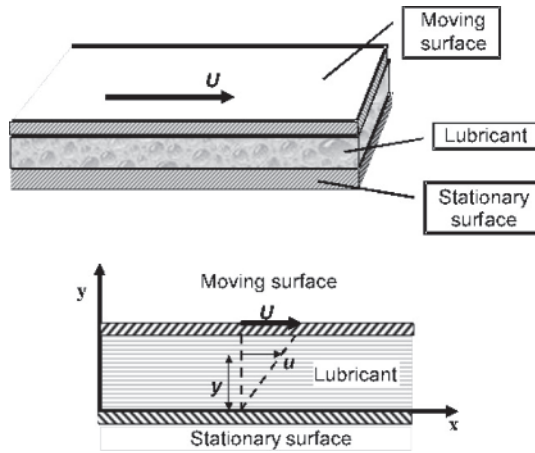
Figure 1.1. *The viscosity "concept"*

A good understanding of the "concept" of viscosity may be gained by examining Figure 1.1, where a plate moves at the uniform velocity U on a lubricant film. This lubricant adheres to both the stationary and the moving surface. The lubricant may be pictured as several layers, each of these being moved by the layer above it at a speed, which is a fraction of the velocity U, proportional to the distance to the moving bounding surface (Newtonian fluid hypothesis). The force F, which needs to be applied in order to move the moving surface, is proportional to the viscosity of the fluid. Therefore, viscosity may be evaluated by measuring this force. Viscosity determined in this manner depends solely on internal friction within the lubricant and is known as dynamic viscosity μ. If at a distance y from the stationary surface the velocity of the particle of fluid is u, then the tangential constraint or the shear constraint τ_{xy} is given, in unidimensional formulation, by:

$$\tau_{xy} = \mu \frac{du}{dy} \qquad\qquad [1.1]$$

The force F is given by the integration of the shear constraint across the film thickness.

The dimensional equation of the dynamic viscosity is:

$$[\mu] = M\,L^{-1}\,T^{-1} \qquad\qquad [1.2]$$

In the International System of Units (SI), the unit used is the Pascal-second (1 Pa.s = 1 kg/(m.s)). In practice, it is very often easier to measure viscosity with equipment where the measurement is influenced by the density of the fluid. A new

unit might, therefore, be introduced, which is the ratio of the dynamic viscosity coefficient to the density of the fluid, named kinematic viscosity, and notated v.

$$v = \mu/\rho \qquad\qquad [1.3]$$

The dimensional equation of the kinematic viscosity is:

$$[v] = L^2 T^{-1} \qquad\qquad [1.4]$$

The unit for kinematic viscosity in the centimeter-gram-second (CGS) system of units is the Stokes (St), but the unit centistokes (cSt) is often used. In the SI system, the unit is expressed in m^2/s (1 cSt = 1 mm^2/s).

In bearings under severe running conditions, viscosity can vary with temperature, pressure and even shear rate.

1.2.1. *Viscosity – temperature relationship*

For oils used in the lubrication of internal combustion engines, viscosity has a decreasing exponential variation with temperature. It drops very rapidly at low temperatures and more slowly at high temperatures. In the literature, there are several analytical approximations of viscosity with temperature [SEE 06]. The following can be used:

– the Reynolds relation:

$$\mu = \mu_0 e^{-\beta(T-T_0)} \qquad\qquad [1.5]$$

where μ_0 is the dynamic viscosity at T_0;

– the McCoull and Walther equation [MCC 21]:

$$\log_{10}\left[\log_{10}\left(v_{cSt} + c_1\right)\right] = c_2 - c_3 \log_{10} T_{\circ K} \qquad\qquad [1.6]$$

where v_{cSt} is the kinematic viscosity in centistokes and $T_{\circ K}$ the absolute temperature. c_1, c_2, and c_3 are constants, which depend on the lubricant;

– the Roelands equation [ROE 66]:

$$\log_{10}\left[\log_{10} \mu_{cP} + 1.200\right] = \log_{10} G_0 - S_0 \log_{10}\left(1 + \frac{T_{\circ C}}{135}\right) \qquad\qquad [1.7]$$

where μ_{cP} is the dynamic viscosity in centipoises (1 cP = 10^{-2} dyn.s/cm^2 = 10^{-3} Pa.s) and $T_{°C}$ is the temperature in °C; G_0, which gives the viscosity grade, and S_0 are dimensionless constants, which depend on the lubricant. This relation can be rewritten in the form [HAM 04]:

$$\mu = \mu_\infty 10^{G_0\left(1+\frac{T_{°C}}{135}\right)^{-S_0}}$$

[1.8]

which directly gives the dynamic viscosity in Pa.s in function of the temperature in °C where $\mu_\infty = 6.31\times10^{-5}$ Pa.s ;

  – the Slotte equation [SLO 81]:

$$\mu = \frac{a}{\left(T - T_c\right)^m}$$

[1.9]

where T_c is the pour temperature, and a and m are coefficients dependent on the lubricant.

The algorithms presented in the chapters which follow may include any model. In the numerical applications, the choice has often been made to use a modified Reynolds relation with a corrective viscosity μ_c:

$$\mu = \mu_0 e^{-\beta(T-T_0)} + \mu_c$$

[1.10]

where μ is the dynamic viscosity at the temperature T, β is the thermoviscosity coefficient, and $(\mu_0 + \mu_c)$ is the viscosity at the temperature T_0.

Figure 1.2 shows the variation of viscosity with temperature for the various laws mentioned above. Note that the modified Reynolds relation is close to the McCoull and Walther law, and also to the Roelands law for viscosities beyond the common point (this corresponds to a temperature of 100°C for this example). Even Slotte's law, despite its simplicity, gives a good evaluation of viscosity. Reynolds' laws, in original form or modified, diverge from the other laws for low temperatures.
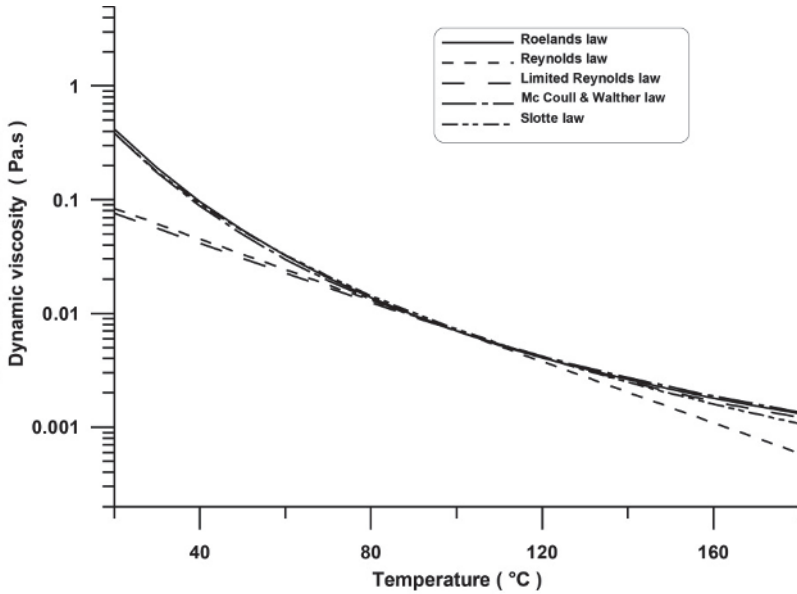
Figure 1.2. *Viscosity variation for SAE 30 engine oil with respect to temperature: Reynolds law:* $\beta = 0.031\ °C^{-1}$; *Roelands law:* $S_0 = 1.5\ G_0 = 4.7$; *Reynolds law with limit:* $\beta = 0.031\ °C^{-}$; $\mu_c = 0.0007\ Pa.s$; *McCoull and Walther law:* $\rho = 840\ kg/m_3$; $c_1 = 1.1131\ cSt$; $c_2 = 10.685$; $c_3 = 4.1589$; *Slotte law:* $Tc = -25\ °C$; $a = 10_6$; $m = 3.88$

1.2.2. *Viscosity – pressure relationship*

Variation in viscosity with respect to pressure can be modeled using one of the following laws:

– the Barus law [BAR 93]:

$$\mu = \mu_0 e^{\alpha(p-p_0)} \qquad\qquad [1.11]$$

where α is the piezoviscosity coefficient (in Pa^{-1}) and μ_0 is the dynamic viscosity at the pressure p_0 and temperature T_0;

– the power law:

$$\mu = \mu_0 \left(1 + ap\right)^b \qquad\qquad [1.12]$$

with two coefficients a (in Pa^{-1}) and b, which are dependent on the physico-chemical properties of the lubricant;

– the Roelands equation [ROE 66]:

$$\log_{10} \mu_{cP} + 1.200 = \left(\log_{10} \mu_0 + 1.200 \right) \left(1 + \frac{p}{2000} \right)^{z_1} \qquad [1.13]$$

where μ_{cP} is the dynamic viscosity in centipoises and p the pressure in $(kg)_{force}/cm^2$ (= 98.100 Pa); μ_0, is the viscosity in centipoises at zero pressure; z_1 is the viscosity-pressure index, a dimensionless constant, which varies between 0.40 and 1.20 and which, for lubricants, does not vary substantially with temperature; this relation may be rewritten in the form [LAR 00]:

$$\mu(p) = \mu_0 e^{\left(\ln \mu_0 + 9.671 \right) \left[-1 + \left(1 + \frac{p}{c_p} \right)^{z_1} \right]} \qquad [1.14]$$

which directly gives the dynamic viscosity in Pa.s in function of the pressure in Pa where $c_p = 1.96 \times 10^8$ Pa.s , and the reference viscosity μ_0 is expressed in Pa.s.

1.2.3. *Viscosity – pressure – temperature relationship*

The relations presented above do not take the simultaneous variations of temperature and pressure into account. For them to be applicable to real lubricants, the coefficients of these relations should also vary with pressure for temperature, and with temperature for pressure.

On the basis of experiments that he conducted, Roelands suggests a combination of the laws [1.8] and [1.14]:

$$\log_{10} \mu_{cP} + 1,200 = G_0 \frac{\left(1 + p/2000 \right)^{C_2 \log_{10} \left(1 + T_{\circ C}/135 \right) + D_2}}{\left(1 + T_{\circ C}/135 \right)^{S_0}}$$

which may be rewritten [LAR 00] as:

$$\mu(p,T) = \mu_0(T) e^{\left[\ln \mu_0(T) + 9.671 \right] \left[-1 + \left(1 + p/c_p \right)^{C_Z \ln(1 + T_{\circ C}/135) + D_Z} \right]} \qquad [1.15]$$

where:

$$\mu_0(T) = 10^{-4.2 + G_0 \left(1 + T_{\circ C}/135 \right)^{-S_0}} \qquad [1.16]$$

Here, the viscosity is in Pa.s, the temperature is in C, and the pressure is in Pa. This law gives the viscosity in function of the four constants G_0, S_0, C_Z and D_Z. Only four experimental measurements are necessary to obtain these constants.

Figure 1.3 shows the viscosity variation of a naphthenic-paraffinic oil (VG32), the coefficients of which are $G_0 = 4.49$; $S_0 = 1.68$; $C_Z = 0.010$ and $D_Z = 0.692$ [LAR 00].
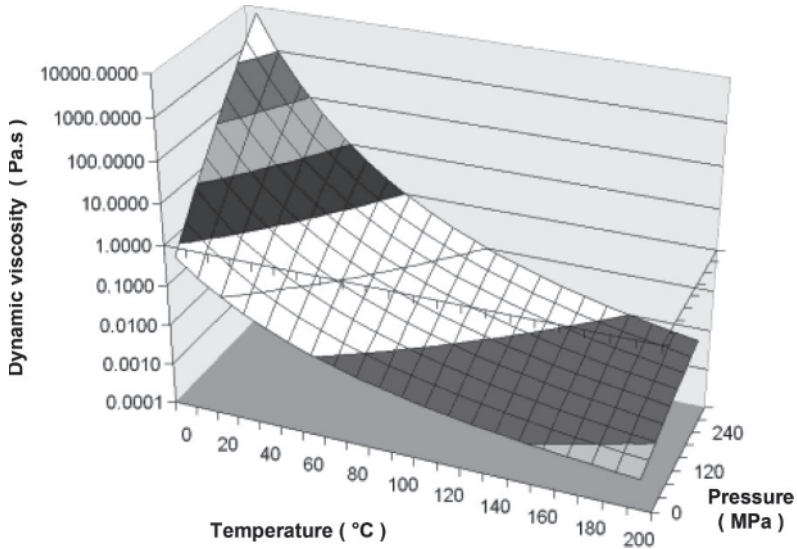
Figure 1.3. *Viscosity variation for a naphthenic-paraffinic oil (VG32) with respect to temperature and pressure*

Relations [1.15] and [1.16] are complex. As a result, Reynolds law [1.5] or modified Reynolds law [1.10] for thermoviscosity and Barus law [1.11] or power law [1.12] for piezoviscosity are more often used for calculations regarding engine bearings. These laws may be combined in several different ways. Figure 1.4 shows that a variation close to that given by the Roelands law may be found (same parameters as for Figure 1.3) if the term for corrective viscosity μ_c is placed outside the product of the thermoviscosity and piezoviscosity factors.
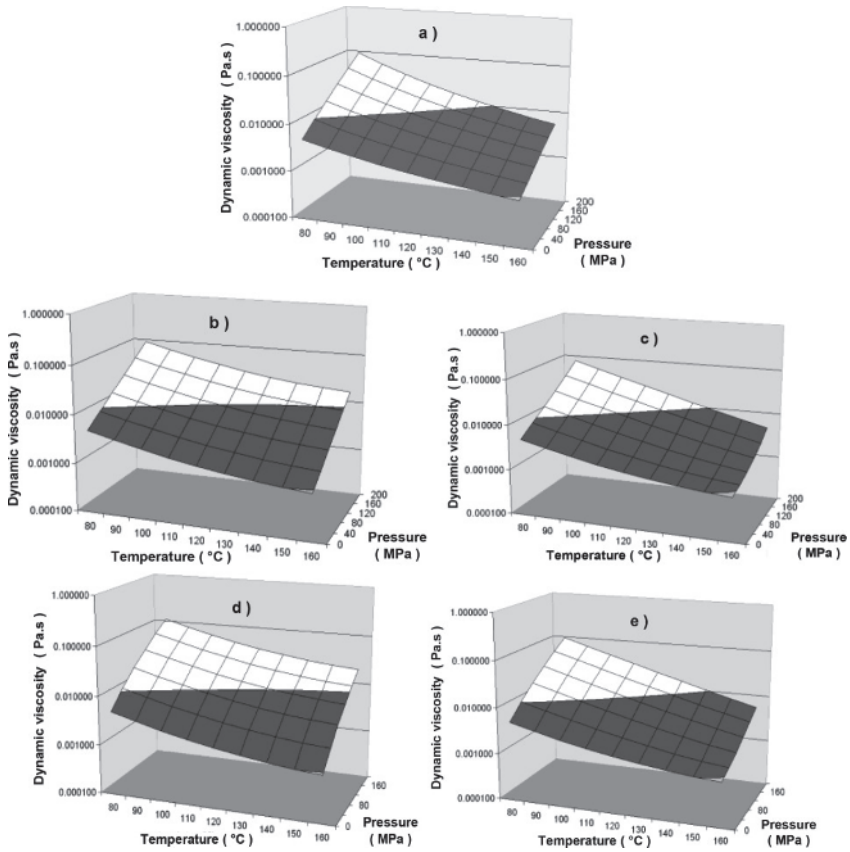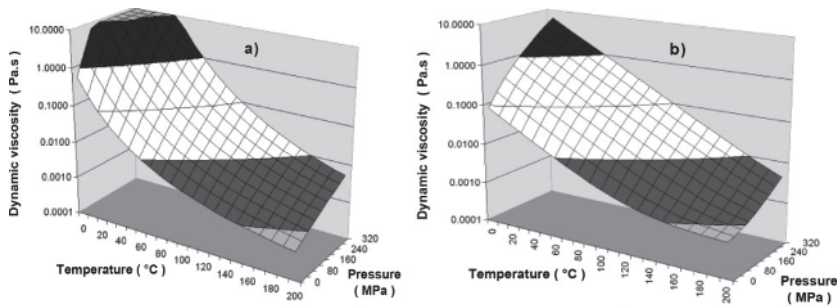
Figure 1.4. *Viscosity with respect to temperature and pressure:a) Roelands law;*

$$b)\ \mu(p,T)=\left[\mu_0 e^{-\alpha(T-T_0)}+\mu_c\right]e^{\beta(p-p_0)}\quad c)\ \mu(p,T)=\mu_0 e^{-\alpha(T-T_0)+\beta(p-p_0)}+\mu_c\ ;$$

$$d)\ \mu(p,T)=\left[\mu_0 e^{-\alpha(T-T_0)}+\mu_c\right]\left[1+a(p-p_0)\right]^b\quad \mu(p,T)=\mu_0 e^{-\alpha(T-T_0)+\beta(p-p_0)}+\mu_c$$

$$e)\ \mu(p,T)=\mu_0 e^{-\alpha(T-T_0)}\left[1+a(p-p_0)\right]^b+\mu_c\quad \mu_0=0.51\ Pa.s\ ;\ p_0=0\ ;\ T_0=80\ °C\ ;$$

$$\mu_c=0.0007\ Pa.s.\ \alpha=0.0375\ °C^{-1};\ \beta=1.43.10^{-8}\ Pa^{-1}\ ;\ a=4.2.10^{-9}\ Pa^{-1}\ ;\ b=5$$

If the pressure in the lubricant becomes significant, the laws presented above give viscosities, which are notably different at low temperatures. Figure 1.5 shows the evolution of the viscosity over a range of temperatures from 0 to 200°C and a range of pressures from 0 to 320 MPa, with the same parameters as for Figure 1.4. At a temperature of 20°C and a pressure of 320 MPa, the Roelands law gives a viscosity of 180 Pa.s, whereas the combination of the Reynolds law corrected for thermoviscosity with the power law for piezoviscosity only gives 4.06 Pa.s. However, in areas of high temperature, the results correspond well.

Figure 1.5. *Viscosity with respect to temperature and pressure:*
a) Roelands law ; b) $\mu(p,T) = \mu_0 e^{-\alpha(T-T_0)} \left[1 + a(p - p_0)\right]^b + \mu_c$

1.2.4. *Non-Newtonian behavior*

The Newtonian fluid hypothesis mentioned at the beginning of section 1.2 presumes that there is a linear variation of the shear constraint τ in relation to the shear rate $\dot{\gamma}$. However, experimental studies have shown that for high shear rates, the assumption of a linear variation of τ with respect to $\dot{\gamma}$ is no longer valid. This is known as non-Newtonian behavior, and it may also be represented by a variation in the dynamic viscosity with respect to the shear rate.

In the bearings of internal combustion engines, the non-Newtonian effect diminishes viscosity when shear rate increases. While this effect is generally reversible, it may also be permanent. If this is the case, the degradation of the lubricant is due to the rupture of certain molecular chains, and especially those of the polymer additives.

Pseudoplastic and viscoplastic fluids (Figure 1.6) feature among the types of fluids often used for lubrication. Threshold fluids (Bingham and Herschel–Bulkey fluids) are rarely considered for the lubrication of engine bearings. In fact, the threshold constraint of these fluids and of fats in particular is very low – at approximately 300 Pa [MUT 86] – when faced with levels of shear constraints within the lubricant film which reach 10^5 Pa.

K and n are rheological characteristics, experimentally determined. The coefficient K is the fluid consistency index, and n is the flow index. Depending on the value of n, fluids may be classified into two groups:

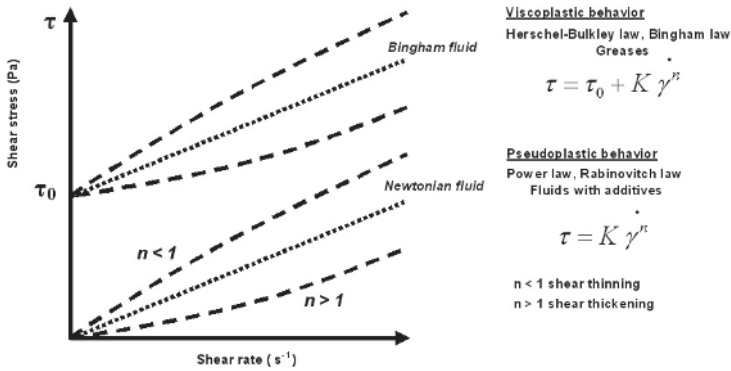– shear thinning fluids for $n < 1$;

– shear thickening fluids for $n > 1$.

Figure 1.6. *Non-Newtonian rheological behavior laws*

Several rheological models have been developed to show these behaviors. The simplest and perhaps the most widely used of these is the Oswald model (also known as the power law) which may be written in the following form:

$$\mu = K \dot{\gamma}^{n-1} \text{ or } \tau = K \dot{\gamma}^n \qquad [1.17]$$

where $\dot{\gamma} = \sqrt{\left(\dfrac{\partial u}{\partial y}\right)^2 + \left(\dfrac{\partial w}{\partial y}\right)^2}$.

The consistency K and the index n are rheological characteristics, which are determined experimentally. For a Newtonian fluid, $K = \mu$ and $n = 1$. This law does not provide a good representation of the variation in viscosity for low or high shear rates.

The Cross equation [CRO 65] describes the non-Newtonian behavior of fluids:

$$\mu = \mu_\infty + \frac{\mu_0 - \mu_\infty}{1+\dfrac{\dot{\gamma}}{\dot{\gamma}_c}} \text{ or } \tau = \left(\mu_\infty + \frac{\mu_0 - \mu_\infty}{1+\dfrac{\dot{\gamma}}{\dot{\gamma}_c}} \right) \dot{\gamma} \qquad [1.18]$$

where μ_0 is the dynamic viscosity at zero shear rate and μ_∞ is the dynamic viscosity for an infinite shear rate. $\dot{\gamma}_c$ is the shear rate at which the viscosity is medium

between μ_1 and μ_2. To achieve a realistic representation, $\dot{\gamma}_c$ should vary with temperature.

A similar equation has been suggested by Gecim [GEC 90]:

$$\mu = \mu_1 \frac{k + \mu_2 \dot{\gamma}}{k + \mu_1 \dot{\gamma}} \quad \text{or} \quad \tau = \left(\mu_1 \frac{k + \mu_2 \dot{\gamma}}{k + \mu_1 \dot{\gamma}} \right) \dot{\gamma} \qquad [1.19]$$

where k is a stability coefficient, which increases with temperature, and μ_1 and μ_2 are respectively the dynamic viscosities at low and high shear rates (Figure 1.7).
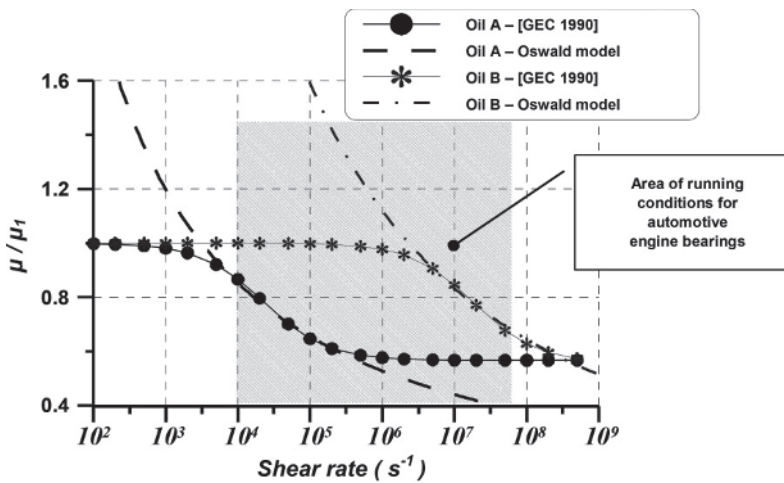
Figure 1.7. *Viscosity variation with respect to shear rate for a 10W40 oil with different additives [GEC 90]: oil A at 75°C: $\mu1 = 0.0245$ Pa.s ; $\mu2 = 0.0139$ Pa.s ; $k = 550$ Pa ; $K = 4.38$ Pa.s ; $n = -0.18$; oil B at 150°C: $\mu1 = 0.0043$ Pa.s ; $\mu2 = 0.024$Pa.s ; $k = 80,000$ Pa ; $K = 34.98$ Pa.s ; $n = -0.92$*

1.3. Other lubricant properties

In the study of lubricated systems, other lubricant properties should be considered, especially if thermal phenomena are taken into account. In order to solve the equation for energy in the lubricant film (see Chapter 3 of [BON 14]), the density ρ, the specific heat C_p and the thermal conductivity coefficient k all need to be known. In much the same way as with viscosity, these parameters vary with temperature.

The variation in density with temperature may be modeled by [LAR 00]:

$$\rho(T) = \rho_{T_0}\left[1 - \lambda_\rho\left(T - T_0\right)\right]$$

[1.20]

where ρ_{T0} is the density at T_0 (in kg/m^3) and λ_ρ is a correction coefficient for the density with respect to temperature (which varies depending on the oil used). This coefficient varies with pressure, following the law:

$$\lambda_\rho(p) = \lambda_{\rho 0} e^{-c(p - p_0)}$$

[1.21]

where c is a constant, which is approximately equal to 1.5 10^{-9} Pa^{-1}, and $\lambda_{\rho 0}$ is the correction coefficient of density with respect to the reference pressure.

The variation in specific heat with respect to temperature and pressure may be written in the following form [LAR 00]:

$$C_p(p,T) = \frac{\rho_0 C_{p0}}{\rho(p,T)}\left[1 + \beta(p)(T - T_0)\right]\left[1 + \frac{a_1(p - p_0)}{1 + a_2(p - p_0)}\right]$$

[1.22]

where C_p is the thermal capacity in J/(Kg.°C) and ρ_0 and C_{p0} are the density and the thermal capacity at the reference temperature and pressure. The parameter β depends on pressure and may be expressed in the form:

$$\beta(p) = \beta_0\left[1 + b_1\left(p - p_0\right) + b_2\left(p - p_0\right)^2\right]$$

[1.23]

The constants a_1, a_2, b_1 and b_2 depend on the lubricant.

The variation in the thermal conductivity coefficient with temperature may be modeled by:

$$k(T) = k_0\left[1 - b_3\left(T - T_0\right)\right]$$

[1.24]

where k is the thermal conductivity in W/(m °C), k_0 is the conductivity of the oil at the reference temperature T_0, and b is a coefficient which is dependent on the lubricant.

The variation in the thermal conductivity coefficient with pressure may be modeled in the same way [LAR 00]:

$$k(p) = k_0 \left[1 + \frac{c_1 (p - p_0)}{1 + c_2 (p - p_0)} \right]$$ [1.25]

the constants c_1 and c_2 depend on the lubricant.

Table 1.1 gives the coefficients of the relations above for two basic lubricants. Values for other lubricants are given by Larsson *et al.* [LAR 00].

				Naphthenic mineral oil				Paraffinic mineral oil			
S_0	G_0	C_Z	D_Z	1.60	5.13	-1.01	0.881	1.31	4.76	0.229	0.541
temperature (°C)				20	20	80	80	20	20	80	80
pressure (MPa)				0	400	0	400	0	400	0	400
α *(GPa^{-1})*				40	35	19	16	26	19	18	14
ρ at 15°C (kg/m³)	λ_{p0} at 40°C (°C⁻¹)			917		6.5 10⁻⁴		884		6.6 10⁻⁴	
k_0 $(W\,m^{-1}\,°C^{-1})$	c_1	c_2	b_3	0.118	1.54	0.33	0.00054	0.137	1.72	0.54	0.00054
T_0 (°C)	$\rho_0\,C_{p0}$ $(J\,m^{-3}\,°C^{-1})$		β_0	22		1.64 10⁻⁶	9.9 10⁻⁴	22		1.71 10⁻⁶	9.3 10⁻⁴
a_1	a_2	b_1	b_2	0.56	0.80	0.58	-0.46	0.47	0.81	1.4	-0.51

Table 1.1. *Coefficients for relations [1.21] to [1.25] for two basic oils [LAR 00]*

1.4. Lubricant classification and notation

There is no single way of classifying and notating lubricants. Each company tends to have its own system for doing this. However, the international classification for industrial oils is the ISO-VG classification, which contains 18 classes. The numerical system attached to a lubricant corresponds to its kinematic viscosity in centistokes (mm²/s) at 40°C (for example, the oil ISO-VG 32 has a kinematic viscosity of 32 cSt at 40°C).

The classification adopted for automobile engine lubricants is that of the Society of Automotive Engineers (SAE). This classification divides the lubricants into two categories: engine oils and transmission oils. In each category, the oils are classified into *grades* according to dynamic viscosity at two reference temperatures: *winter temperature* (0°F = - 17.8°C) and *summer temperature* (210°F = 100°C). In addition, SAE oils may be divided into two categories:

– *monograde oils*: the variation in viscosity corresponds to an SAE grade;

– *multigrade oils*: the viscosity only varies slightly with temperature (these oils contain additives which improve the viscosity index); as a result, these oils are classified with two SAE grades, one of which must contain the letter *W* (winter). When an oil has two SAE grades, which have an indication of *W*, the lowest of these should be used.

Table 1.2 shows the SAE classification of engine oils.

SAE grade	Kinematic viscosity at 100°C [cSt]		Dynamic viscosity [Pa.s] at minimum running temperature
	Minimum	Maximum	
0W	3.8	–	32.5 at – 30°C
5W	3.8	–	35 at – 25°C
10W	4.1	–	35 at – 20°C
15W	5.6	–	35 at – 15°C
20W	5.6	–	45 at – 10°C
25W	9.3	–	60 at – 5°C
20	5.6	9.3	–
30	9.3	12.5	–
40	12.5	16.3	–
50	16.3	21.9	–
60	21.9	26.1	–

Table 1.2. *SAE classification for engine oils*

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