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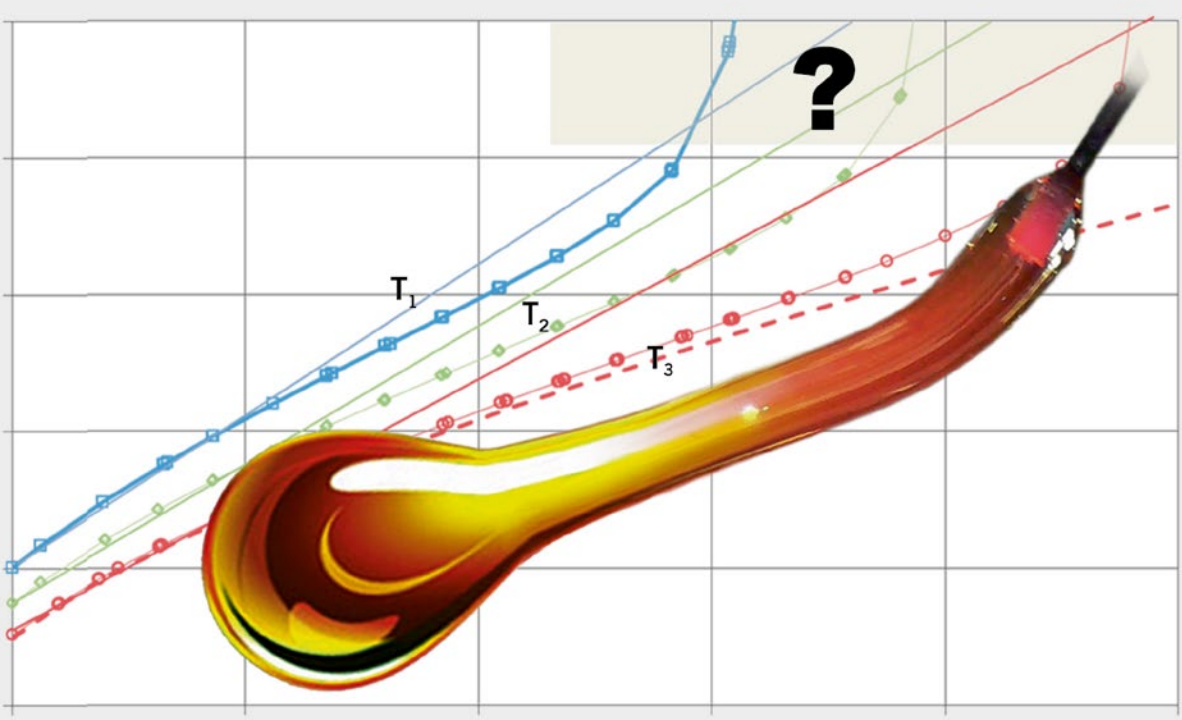
Tribological Fluid Models for Ancillary Units in Electrical and Hybrid Motor Vehicles

In the ancillary units on electrical and hybrid motor vehicles, tribological contacts are often subject to severe stresses. A decrease in the associated frictional losses is thus a vital objective for increasing the efficiency of these vehicles. In the calculation programs employed for computer-aided optimising of the components involved, the lubricant as a machine element must generally be represented by a fluid model. Under the conditions which prevail in EHL contacts subject to severe stress, the lubricant assumes a solid or vitreous state, which cannot be correctly described in terms of Newtonian viscosity. For allowing the consideration of the lubricant as a machine element in calculation programs even under such extreme conditions, special fluid models are required for adequately describing the flow behaviour. Fluid models of this kind have been developed and validated as a cooperative effort by ITR, IMKT, and IMK within the scope of an FVV research project.



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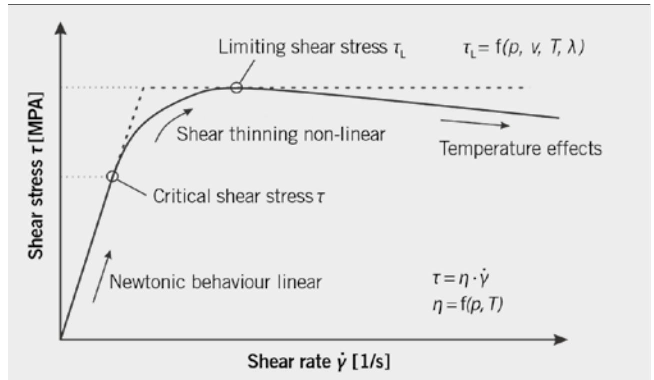

FIGURE 1 Dependence of the shear stress on the flow behaviour of a fluid (© ITR)

1 MOTIVATION

Fluid models have been developed for allowing a more accurate consideration of the lubricant as a construction element in designing the ancillary units on electrical and hybrid motor vehicles. With the use of these models, the fluid properties measured under static conditions in the laboratory can be represented in an appropriate form for calculation programs, with due consideration of results from the test stand. For this purpose, a research project initiated by the FVV Work Group on Tribology and Motor Fuels has been executed by the three aforementioned institutes. The objectives of the present article are to indicate the problems involved, to explain the approach for obtaining an appropriate solution, and to describe the essential results.

2 FLUID MODEL

The purpose of a fluid model is to describe the behaviour of a fluid under operational conditions [1], [2], [3] and [4]. During practical applications, temperatures between 0 and 250 °C, pressures up to 3300 MPa, and in some cases nominal shear rates exceeding 10^7 s^{-1} are likely to occur in the contact. In **FIGURE 1**, the shear stress is plotted as a function of the shear rate for different flow behaviour of a fluid. The shear stress increases linearly in the Newtonian range, becomes progressively more nonlinear in the following range, and then approaches a limiting value asymptotically. Since the temperature cannot be held constant during experiments at high shear rates, the shear stress attains a maximum and then decreases. The flow behaviour is controlled by the viscosity η_0 in the Newtonian range, by the critical shear stress τ_c in the nonlinear range, and by the limiting shear stress τ_{lim} at high shear rates. These values in turn depend on the pressure and temperature.

At the present state of the art, it is often not possible to measure characteristic parameters for a lubricant under extreme operational conditions. In particular, it is still not possible to perform measurements simultaneously under high pressure and at high shear rates. For conditions which are not accessible with the present measuring technology, the values are extrapolated with due consideration of the flow behaviour. The dependence of the viscosity on the shear rate is described with the use of a flow model which constitutes the fluid model, together with the models for the density, viscosity, specific heat capacity, and thermal conductivity [5]. For describing the flow behaviour above the nonlinear range, a limiting shear stress has been implemented in the mod-

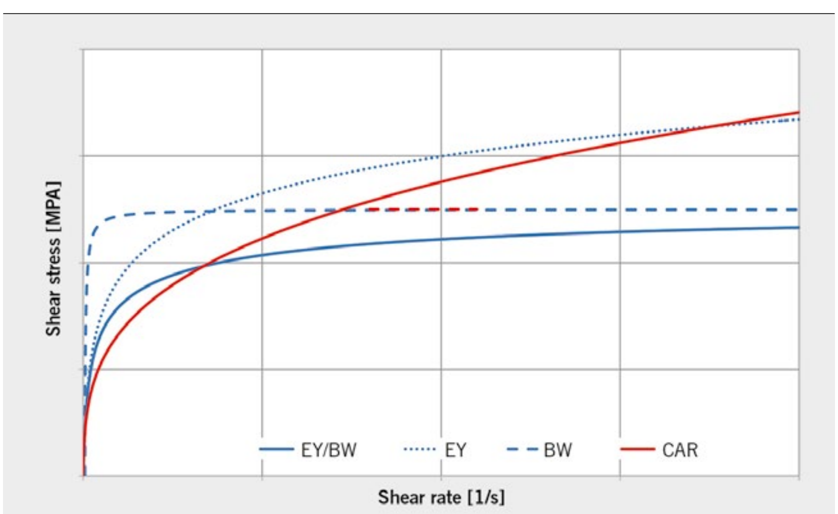

FIGURE 2 Flow models (characteristic curves) (© ITR)

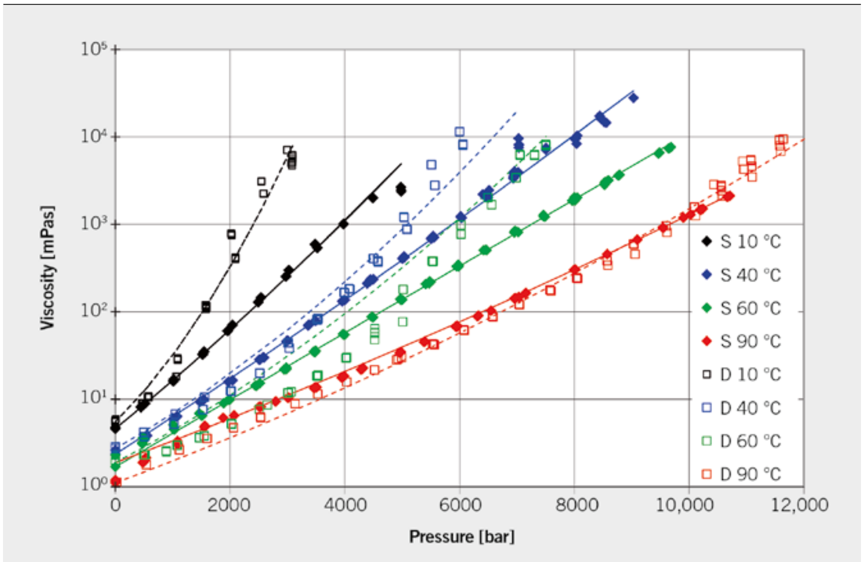

FIGURE 3 Dependence of the viscosity on the pressure and temperature for two diesel fuels (© ITR)

elling approaches of Eyring (EY) and Carreau (CAR). In the case of the Eyring model, this objective is achieved by a combination with a simplified Bair/Winer (EY/BW) model. In the case of the Carreau model, the shear stress is limited by wall slip, which is introduced for reasons of consistency (CAR+BW). The resulting flow models are illustrated in **FIGURE 2**. Both models are capable of describing the non-Newtonian behaviour by means of the critical shear stress τ_c and the limiting shear stress τ_{lim}.

3 EXPERIMENTAL RESULTS

The thermophysical properties of lubricants and motor fuels have been determined as functions of the pressure, temperature, and shear rate. Furthermore, the frictional characteristics have been investigated in a high-pressure chamber (HPC) at pressures which correspond to the compression exerted on functional test stands [6]. In **FIGURE 3**, the viscosity is plotted as a function of the pressure for two diesel fuels at temperatures between 10 and 90 °C. From these measurements, limiting shear stresses have been derived for static conditions in accordance with thermodynamic principles [7].

By means of traction measurements on a two-disc test stand and on an MTM tribometer, the frictional force was determined as a function of the compression and slip. On the one hand, this result can be employed for validation of the simulation. From traction curves, **FIGURE 4**, on the other hand, the maximal fluid-typical shear stress which can be transmitted through the fluid was determined as a function of the compression [8]. With the exception of one braking fluid, all fluids under investigation exhibited an approximately linear relationship between the compression and maximal shear stress within the measuring range. The integral limiting shear stresses were determined under dynamic conditions for the pressure and temperature distribution in the EHD contact. These values correlate very well with those which were measured under

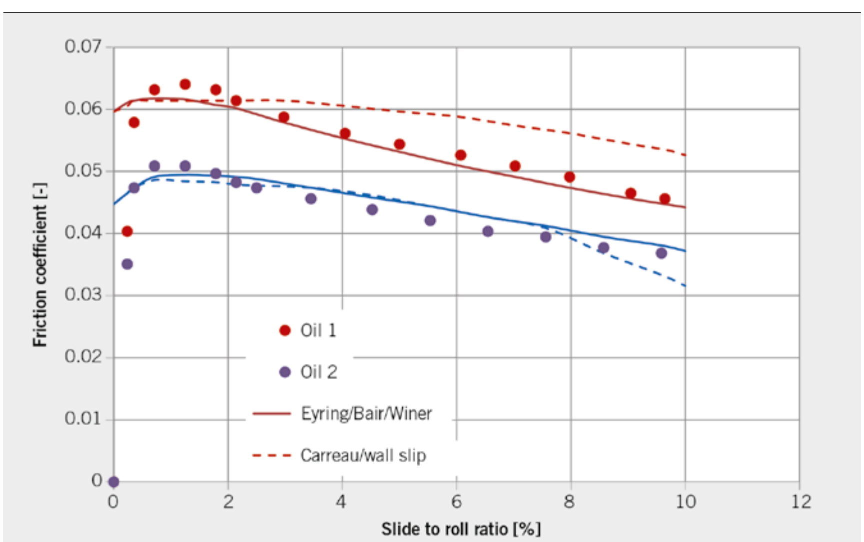

FIGURE 4 Comparison between experiment and simulation (traction curves at 60 °C, 10 m/s, 1420 MPa) (© ITR)

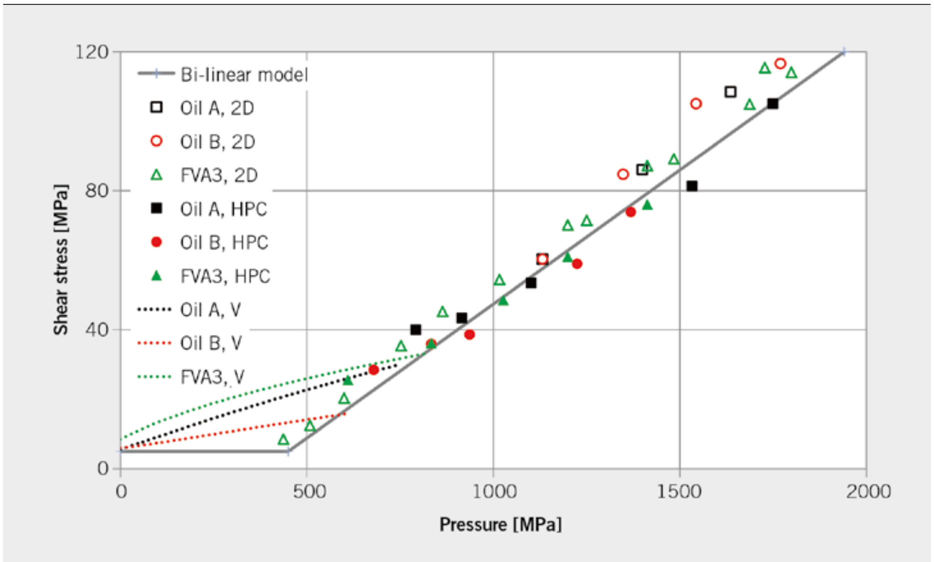

FIGURE 5 Dependence of the limiting shear stress on the pressure (© ITR)

stationary conditions at defined values of the pressure and temperature, **FIGURE 5**. The limiting shear stresses derived from the viscosity measurements at pressure or compression values below 500 MPa indicate that the linear variation toward lower pressure does not continue further. The limiting shear stress also remains positive at low pressure; this observation certainly makes sense physically. In the fluid model, the dependence on the pressure is approximated by a bilinear approach, **FIGURE 5**. In order to validate the fluid models at low shear rates, too, the lubricant film thickness was also measured as a function of the velocity and temperature on a ball-on-disc tribometer for all fluids, in addition to the traction measurements.

4 SIMULATION

The traction curves determined on the two-disc test stand and with the MTM tribometer, as well as the lubricant-film-width measurements performed with the ball-on-disc tribometer, have been employed as a basis for developing an appropriate fluid model for simulation calculations. The tribologically relevant components have been implemented in numerical 3-D-TEHD simulation software [9]. For the two-disc tests, the traction behaviour was calculated with due consideration of the real load, the rotational speed, the macro- and microgeometry of the discs, the mass temperature of the discs, as well as the measured high-pressure-rheometric lubricant properties. By means of numerical calculations, the criteria for an appropriate fluid model have been determined. In the course of the project, a total of eight flow models have been tested. However, three of these models were not considered further because they were not suited for numerical implementation.

Besides the pressure dependence of the viscosity from the measurements performed with the high-pressure viscometer, flow models have been integrated with a very wide non-Newtonian transition range, in order to allow adequate modelling of the shear dilution, including the limiting shear stress. For obtaining good agreement between simulation and experiment, the shear stress must already be limited in the flow model. Consequently, the Eyring and Carreau models cannot yield the desired results, any more than the Bair/Winer model, which does not correctly describe the nonlinear range. The extrapolation of the pressure dependence of the limiting shear stress from values measured at high pressures formally results in negative values, and thus in numerical instabilities in the simulation. Therefore, a bilinear approach

Eq. 1 $$\tau_{max} = \tau_{max,0} \text{ for } p \leq p_0$$

Eq. 2 $$\tau_{max} = (p - p_0) \cdot \beta \text{ for } p > p_0$$

has been implemented in the flow model, **FIGURE 5**.

For mineral oils, PAO, diesel fuel, and similar hydrocarbons, $\tau_{max,0} \approx 6$ MPa, $\beta \approx 0.08$, and $p_0 \approx 400$ MPa. In the case of polyglycols, such as the braking fluid under investigation, the values of the parameters deviate.

With the two flow models developed in this study, the comparison between experiment and simulation indicates good agreement over a wide range, for variations in load, rotational speed, slip, and temperature, **FIGURE 4**. Calculations of the lubricant film thickness likewise yielded good agreement for corresponding experiments. These experiments were performed under conditions (low slip, moderate pressure), under which the lubricant film thickness is determined mainly by the pressure dependence of the viscosity. From the traction measurements, relationships between compression and shear stress have been derived for various types of geometry – disc-disc and ball-disc. These relationships are simulated comparatively well.

No unambiguous effect of the temperature on the maximal shear stress could be derived from the measurements. Under the non-isothermal test conditions, an estimate of the lubricant-film temperature from the available values from the measurements (oil-intake temperature and outer ring temperature) is not sufficiently accurate for determining the relatively weak temperature dependence. The investigation of the temperature effects is therefore an especially important task for the future.

The original Eyring model is not well suited for describing the flow behaviour of real fluids, since the spread of the nonlinear range is insufficient, and there is no limitation on the shear stress. By means of a combination with the simplified Bair/Winer model, these essential disadvantages are eliminated. In the Carreau model, a limitation on the shear stress is introduced, as described in the literature, in order to extend the validity beyond the nonlinear range. The essential parameters of both models can be derived from the traction measurements and friction measurements in the high-pressure chamber.

The range in which the fluids are able to transmit forces (shear stresses) can be subdivided into two sections. At low to moderate pressure, the viscosity increases degressive-exponentially with the pressure, and the maximal shear stress exhibits a slight dependence on the pressure. In this range, the pressure dependence of the viscosity is controlled essentially by the frictional properties of the fluid. At extreme pressures, the viscosity increases progressive-exponentially. For most fluids, the pressure dependence of the limiting shear stress (coefficient of friction) approaches a value of 0.08, which is typical for many concentrated tribological contacts (solid friction). In this range, the frictional properties are dominated by the limiting shear stress. Consequently, the extremely high viscosity values determined by the laboratory measurements are of no importance.

Over almost all operating points, the calculated coefficients of friction were too high in comparison with the measured values in the very-low-slip range with both flow models. Elastic properties or a time dependence of the viscosity are currently under discussion as possible causes of this deviation. Both phenomena are the object of future investigations.

5 SUMMARY

On the whole, the results of the present investigation indicate that the 3-D-TEHD simulation model applied here is well suited for calculations on lubricated, concentrated contacts. For the lubricant-gap width, excellent agreement with measured values has been achieved. In most cases, very good results were achieved for the traction behaviour with the use of high-pressure rheometric data and by adjustment with the results of traction tests in accordance with the workflow developed with a few flow models.

REFERENCES

[1] Bair, S.; Qureshi, F.: The Generalized Newtonian Fluid Model and Elastohydrodynamic Film Thickness. Journal of Tribology (2003), Vol. 125 1, pp. 70-75
[2] Bode, B.: Modell zur Beschreibung des Fließverhaltens von Flüssigkeiten unter hohem Druck. Tribologie + Schmierungstechnik (1989), Vol. 36, pp. 182-189
[3] Habchi, W.; Bair, S.; Vergne, P.: On friction regimes in quantitative elastohydrodynamics. Tribology International (2013), Vol. 58, pp. 107–117
[4] Wang, D.: Berechnung der Wälzlagerreibung aufgrund weiterentwickelter Rheologischer Fluidmodelle. Leibniz Universität Hannover, Dissertation, 2015
[5] Beilicke, R.; et. al.: Tribologische Fluidmodelle zur Simulation der Reibung in geschmierten konzentrierten Kontakten. 56. Tribologie Fachtagung 2015, Göttingen, Vol. I,5/14
[6] Jacobson, B.: High-pressure chamber measurements; Proceedings of the In-stitution of Mechanical Engineers. Part J: Journal of Engineering Tribology (2006), Vol. 220, No. 3, pp. 199-206
[7] Schwarze, H.; Brouwer, L.: Bestimmung der Grenzschubspannung von Schmierstoffen aus Viskositätsmessungen. 54. Tribologie Fachtagung 2013, Göttingen, Vol. I, 1/19
[8] Poll, G.; Wang, D.: Fluid rheology, traction/creep relationship and friction in machine elements with rolling contacts, Proceedings of the Institute of Mechanical Engineers. Part J: Journal of Engineering Tribology (2012), No. 6, pp. 481-500
[9] www.tribo-x.de

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