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Generalized Newtonian viscosity functions for hydrodynamic lubrication

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ABSTRACT

Among some of the generalized Newtonian viscosity functions used in hydrodynamic lubrication, the Cross and Ellis equations have a transition from the first Newtonian plateau to the power-law regime that is much broader than is typical of polymer-thickened oils. The Dobson method employs the Cross equation to extract the second Newtonian viscosity for a polymer-thickened oil from ambient pressure viscometry. This method will always produce a second Newtonian viscosity for a polymer thickened oil, even if none is present in the data. Shear-thinning measured at elevated pressure removes this issue.

An improved viscosity function is offered which describes the shear-dependence of the polymer and of the base oil without the artifacts associated with a sum of individual viscosity equations.

1. Introduction

For the low-pressure applications of hydrodynamic lubrication (HL), such as journal bearings, it has long been appreciated [1–3] that shear dependence of viscosity, shear-thinning, can play an important role in film thickness, pressure profile and friction. It was much later that the effect of shear-thinning on the film thickness in elastohydrodynamic lubrication (EHL) was even considered [4,5]. Prior to that time, most non-Newtonian response in EHL was attributed to thixotropy in the form of the simple Eyring model. See for example, [6]. However, over the last ten years in comparison with HL, progress in applying the generalized Newtonian model to EHL has been rapid [7–11] by employing viscosity functions validated by viscometer measurements. Part of the advantage enjoyed in EHL research results from the small isolated contact for which film thickness and friction can easily be measured. The other aspect, that of very high pressures, facilitates the observation of shear-thinning response. At high pressure, shear cavitation is completely avoided and the viscosity will reach high values. There is a critical shear stress above which the viscosity becomes shear dependent. Without a large value of viscosity, the shear rate must be large to exceed the critical stress and high shear rate leads to viscous heating which bedevils viscosity measurements.

Shear-thinning is not the only type of non-Newtonian behavior observed in lubricants. Thixotropy may be present in liquid lubricants, particularly paraffinic mineral oils. A solid structure forms from a component of the oil when the temperature is low or the pressure is high. In Fig. 1 there are two flow curves for the Tannas shear-thinning reference oil, NNR-03, used for calibrating high shear viscometers [12]. The solid curves are a modification of the Carreau equation [7] for shear-thinning to be discussed later. These curves appear to be approaching a second Newtonian plateau with viscosity, μ_2, of 2.6 and 5.0 Pas at pressures of 200 and 350 MPa, respectively, although the second Newtonian viscosity is likely to be affected by wax structure. For shear stress less than about 1 kPa, the viscosity is time dependent and shear dependent. Viscosity increases with time as the solid structure forms and decreases with shear as the structure is disrupted. Measurements at lower stress take more time and are more affected by the solidification. This behavior can be unfortunate since low temperature or high pressure allows deeper penetration of the shear-thinning regime of flow without encountering thermal softening.

Shear-thinning oils are also shear dependent in oscillatory shear [13]. Shear-thinning oils produce a difference in normal stresses as well that does not occur in Newtonian liquids. The normal stress in the flow direction is more tensile than the stress in the cross-flow direction [14] and this first normal stress difference, N_1, becomes comparable to the shear stress at the limit of Newtonian response. There is a stress overshoot at the start of shear and the viscosity in elongational flow may exceed that of a Newtonian oil [15]. The constitutive equation used in nearly all lubrication analyses does not address these other aspects of shear-thinning liquids, only the shear dependence of the viscosity, hence the terminology, generalized Newtonian model. The Navier-Stokes equations and, therefore the Reynolds equation, apply for a generalized Newtonian liquid but not for the more complete non-Newtonian constitutive models. For shear stress greater than about 5 MPa, the viscosity may also be permanently reduced by mechanical degradation of the polymer [11].

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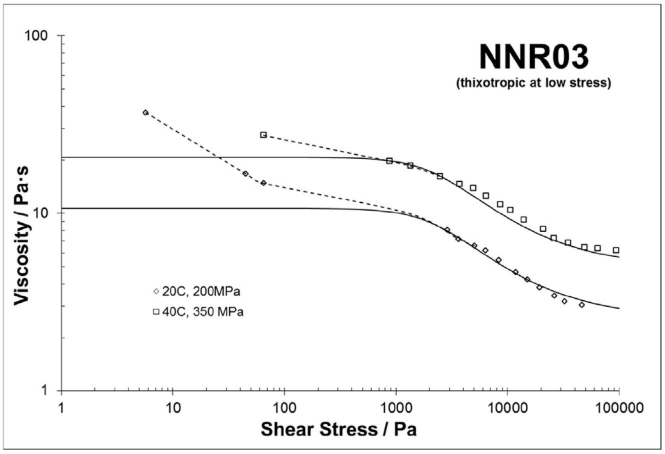

Fig. 1. Elevated pressure flow curves for a reference liquid, Tannas NNR-03, showing thixotropy at low stress. The solid curve is the Modified Carreau equation and the dashed curve is meant as a guide to the eye for the thixotropic data.

Superposition, which is demonstrated in Fig. 2 for a motor oil, is an incredibly useful property of shear-thinning liquids and is essential for analyses of lubrication in bearings. The rapid progress in quantitative elastohydrodynamics [4,5,7–11] would not have been possible without invoking superposition. On a double log plot, flow curves of viscosity versus shear stress, τ, (or the product of the low shear viscosity, μ, and shear rate, γ) can be made to reasonably superimpose by shifting vertically along the viscosity axis. The required shift can be accomplished by simply plotting the ratio of the generalized viscosity, η, to the low-shear viscosity, μ, against τ as in Fig. 2. Plotting η/μ against $\mu\gamma$ will also produce a master curve. If η/μ is a function of $\tau = \eta\gamma$ then it must also be a function of $\tau/(\eta/\mu) = \mu\gamma$. The master curve in Fig. 2 includes a state for which the shear stress reached to 17 MPa. The high stress was possible because the viscosity at 600 MPa is 10^4 Pas. Two transitions are clear, one for the polymer thickener at $\tau \approx 3$ kPa, and one for the base oil at $\tau \approx 6$ MPa. The curve represents a Double Modified Carreau-Yasuda equation to be discussed later.

Because of superposition, the problem of specifying a viscosity function, $\eta = F(T,p,\tau)$ or $\eta = F(T,p,\gamma)$ can be simplified to $\eta = F(\mu(T,p),\tau)$ or $\eta = F(\mu(T,p),\gamma)$ and many quite accurate forms are available for $\mu(T,p)$ such as free volume [16], thermodynamic scaling [16] and Yasutomi [17]. Appropriate forms of viscosity functions are the subject of this article. The author has forty years of experience in applying viscosity functions to lubricating liquids using various types of viscometers. The viscometers employed here to penetrate far enough into the shear dependent regime to shear thin the base oil are of the circular Couette type. The cylinders are made of dispersion-strengthened copper which has good strength and high thermal conductivity. The shearing gap is from 2 to 7 μm and rotation is limited to one revolution. The torque sensor resides in the high pressure environment, immersed in a low viscosity pressurizing medium.

2. Viscosity functions employed in lubrication

For the comparison of viscosity functions and to facilitate superposition, it will be useful to define some properties of shear dependent liquids in a uniform fashion. For the discussion of shear response consider the usual presentation of generalized viscosity versus shear rate or stress on a double log plot. First, consider liquids with no second Newtonian plateau like that seen in Figs. 1 and 2 or no visible inflection suggesting a second plateau. Some motor oils and most gear oils do not reach an inflection before the shear thinning of the base oil.

Without a second Newtonian there will be two asymptotes, a limiting low shear plateau with $\eta \equiv \mu$ and a shear dependent power-law appearing as a straight line with slope $1-1/n$ when the independent variable is shear stress and $n-1$ when the independent variable is shear rate. The rate sensitivity coefficient is $\hat{n} = \min(d\ln\tau/d\ln\gamma)$ and, for $\mu_2 = 0$, $\hat{n} = n$. The intersection of the asymptotes occurs at $\tau = \eta\gamma = G$.

To give some physical meaning to G, consider that μ/G is a characteristic time for shear dependent flow. This characteristic time has been associated with the relaxation time from linear viscoelasticity [15] which would make G a shear modulus. In any event, G is much smaller than the infinite frequency shear modulus measured by transverse ultra sound [18] and less than the ratio of viscosity to relaxation time measured by dielectric spectroscopy [19] as both are of order 1 GPa for simple liquids, such as base oils, for which the Newtonian limit, G, is of order 0.01 GPa. However, an estimate of G can be had from molecular theory [15].

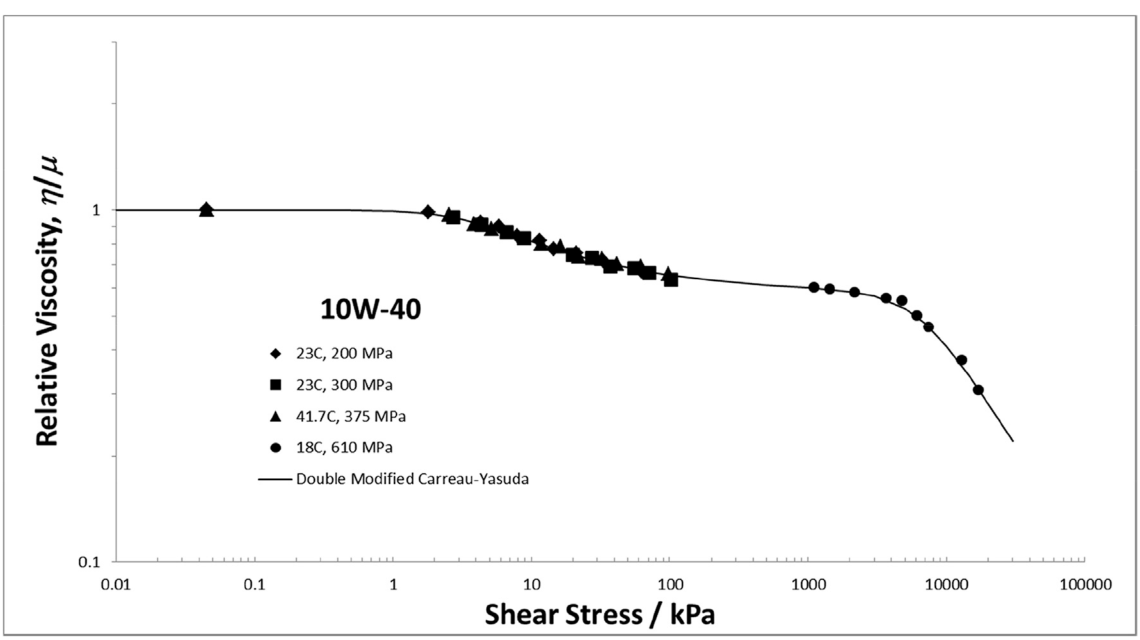

Fig. 2. Superposition of flow curves for a motor oil.