

$$\left. \frac{dT}{dp} \right|_{\mu} = A + B(T - T_r) = - \frac{\frac{1}{\mu} \frac{\partial \mu}{\partial p} \Big|_T}{\frac{1}{\mu} \frac{\partial \mu}{\partial T} \Big|_p} = - \frac{\alpha}{\beta}$$

where A is the value of dT/dp at reference temperature T_r and B is the slope of the curve in Figs. 16 or 17. The temperature viscosity coefficient at atmospheric pressure can be determined at any temperature by standard kinematic viscosity measurements or determined from the slope of an ASTM chart (it is not the slope but related to it). Two viscosity pressure isotherms would, for example, be necessary to determine A and B from which the pressure viscosity coefficient could be predicted for other temperatures.

Although the above data, and apparent relationships, may not be precise, they do suggest that there may be many ways of obtaining an approximate mapping of the low shear viscosity, the relaxation times, shear moduli, temperature and pressure viscosity coefficients, and transition behavior of lubricants from a minimum amount of data. Many of these can then be used to estimate whether a given lubricant will behave as an amorphous solid in a given EHD contact and therefore indicate which type of mechanical shear behavior of the material is most relevant for the application: low shear viscosity or ultimate shear stress of the amorphous solid.

Conclusions

Several measurements of lubricant behavior under pressure have been made to map the liquid-solid behavior transitions. The various methods including mechanical and electrical properties agree well and show the dependence of the transition on pressure and frequency (or rate).

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References

- 1 Alsaad, M., Bair, S., Sanborn, D. M. and Winer, W. O., "Glass Transitions in Lubricants: Its Relation to Elastohydrodynamic Lubrication (EHD)," *ASME JOURNAL OF LUBRICATION TECHNOLOGY*, Vol. 100, July 1978, pp. 404-417.
- 2 Alsaad, M. A., Winer, W. O., Medina, F. D., and O'Shea, D. C., "Light-Scattering Study of the Glass Transition in Lubricants," *ASME JOURNAL OF*

LUBRICATION TECHNOLOGY, Vol. 100, July 1978, pp. 418-422.

3 Johnson, K. L., and Roberts, A. D., "Observations of Viscoelastic Behavior of an EHD Lubricant Film," *Proc. Royal Society of London*, Vol. A337, 1974, p. 217.

4 Johnson, K. L., Discussion of Paper entitled: "Glass Transitions in Lubricants: Its Relation to Elastohydrodynamic Lubrication (EHD)," by Alsaad, Bair, Sanborn and Winer, *ASME JOURNAL OF LUBRICATION TECHNOLOGY*, Vol. 100, July 1978, pp. 404-417.

5 Bair, S., and Winer, W. O., "Shear Strength Measurements of Lubricants at High Pressure," *ASME JOURNAL OF LUBRICATION TECHNOLOGY*, Vol. 101, July 1979, p. 251.

6 Bair, S., and Winer, W. O., "A Rheological Model for Elastohydrodynamic Contacts Based on Primary Laboratory Data," *ASME JOURNAL OF LUBRICATION TECHNOLOGY*, Vol. 101, July 1979, p. 258.

7 Harrison, G., *The Dynamic Properties of Supercooled Liquids*, Academic Press, 1976.

8 *ASME, Pressure-Viscosity Report I, II*, A report prepared by the ASME Research Committee on Lubrication, New York, ASME, 1953.

9 McKinney, J. E., and Goldstein, M., "PVT Relationships for Liquid and Glassy Poly(Vinyl Acetate)," *Journal of Research of the NBS-Physics and Chemistry*, 78A, 331, 1974.

Appendix

Experimental material description for those materials employed in this paper and not described in reference [1].

Symbol	MCS-418	
Type:	Modified Polyphenyl Ether (C-ether)	
Source:	Monsanto Company	
Properties:	Viscosity at 38C, m ² /s	25 × 10 ⁻⁶
	Viscosity at 99C, m ² /s	4.1 × 10 ⁻⁶
	Density at 38C, kg/m ³	1180
	Density at 99C, kg/m ³	1140
	Pour Point	-29
Symbol:	FYRQUEL 150 R & O	
Type:	Tri-Aryl Phosphate	
Source:	Stouffer Chemical Company	
Properties:	Density at 15.6C, kg/m ³	1165
	Pour Point	-23
	Viscosity at 37.8C, Ns/m ²	36.9 × 10 ⁻³
	Viscosity at 98.9C, Ns/m ²	4.83 × 10 ⁻³
Symbol:	Krytox 143-AB (Lot 10)	
Type:	Perfluorinated polyether	
Source:	DuPont Company	
Properties:	Viscosity at 37.8C, m ² /s	96.6 × 10 ⁻⁶
	Viscosity at 98.9C, m ² /s	11.5 × 10 ⁻⁶
	Density at 24C, kg/m ³	1890
	Density at 98.9C, kg/m ³	1760
	V.I. (ASTM D-2270)	116
	Pour point, C	-40
	Flammability	does not burn

DISCUSSION

J. F. Dill²

This article brings out the fact that there are many techniques which can and must be used to most effectively obtain needed viscous relaxation data in liquid lubricants. In some situations and some materials, one technique may be preferable because of greater experimental ease than another. The proportionality of the dielectric relaxation time to the shear viscous relaxation time, i.e., η_s/G_ω , has been pointed out previously by a number of authors (10, 11, and 12). There may be more detailed references on this subject. The three authors I mentioned are some I just happen to know. Although there are advantages and disadvantages to all of the existing techniques for studying viscoelastic relaxation, dielectric relaxation does offer the advantage of providing measurements in a frequency range from 1-100 KHZ which corresponds to a relaxation time range on the order

of magnitude of EHD contact transit times (i.e., 10⁻³-10⁻⁵ s). One disadvantage of dielectric measurements is the question of the proportionality constant between the dielectric data and the shear viscous relaxation time. The proportionality constant between the dielectric time in the data presented in reference [11] is approximately 15, while that in reference [10] is approximately 1.8. While the dielectric relaxation time is proportional to the shear viscous relaxation time, the proportionality constant depends on the liquid under study and must be determined along with the relaxation time. In cases where viscosity data are not available, dielectric relaxation could be a useful technique for estimating average relaxation times, however, since a relaxation spectrum must be measured before the average relaxation time can be obtained, it would seem that in general, it would be easier to measure viscosity to obtain relaxation time estimates.

Additional References

- 10 Litovitz, T. A., and McDuffie, G. E., "Comparison of Dielectric and Mechanical Relaxation in Associated Liquids," *J. Chem. Phys.*, Vol. 39, No. 3, 1 Aug. 1963, pp. 729-734.

² Air Force Aero Propulsion Laboratory Wright-Patterson AFB, Dayton, Ohio 45433.

11 Lamb, J., "Viscoelastic and Ultrasonic Relaxation Studies Related to Molecular Motions in Liquids," in *Molecular Motions in Liquids*, (Ed.) J. Tascombe, D. Reidel Publishing, 1974.

12 Lamb, J., Discussion of "Theory of Rheology," by J. F. Hutton, p. 187 in *Interdisciplinary Approach to Liquid Lubricant Technology*, NASA-SP-319, 1972.

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The similarity of the frequency dependence of the dielectric constant and the complex compliance of dielectric fluids has been known for a long time. Although dielectric "relaxation" should, by analogy with mechanical behavior, be termed dielectric "retardation," as Harrison [13] has pointed out, the semantics has never presented any difficulty of understanding, as it will not for Bair and Winer's excellent paper. However, similar frequency dependence does not necessarily imply identical or near identical glass/liquid or glass/rubbery state transitions, since the reasons for dielectric and mechanical frequency resonances can be quite different. As long as the fluid has a permanent dipole moment, even a small one such as that of the polyphenyl ether fluid (5P4E) used by the authors, the mechanical/electrical analogy of transitions is not difficult to perceive. On the other hand, the dielectric frequency spectrum of the naphthenic mineral oil (N1) is likely to have its origin in small oxidations of various molecular branches [14] and could be different from the mechanical frequency spectrum. Its temperature behavior could also be different, since a distribution of relaxation times rather than a single relaxation time is likely to exist. Did the authors indeed obtain a frequency spectrum of multiple absorptions for N1? Did the authors compare the dielectric behavior of fresh and used N1 (the former could be more lightly oxidized)? The authors show dielectric permittivities and loss tangents for different frequencies as a function of temperature for 5P4E (Figs.

5 and 6), but not for N1. It would be interesting to be able to compare the trends for 5P4E with those of N1.

By the way, similar transition temperatures of permittivity and loss tangents are to be expected since these quantities are not independent, but related by the Kramers-Kronig equations (the authors might have pointed this out).

Perhaps the most important contribution of the paper is the reference to possible derivations of pressure-viscosity coefficients from viscosity changes with temperature from series of curves, which also may involve transition behavior. Similar attempts have been made previously, but not by the authors' prescription. I would like to call the authors' attention to the work of Stearns et al., [15] who were able to show that glass transition temperatures of many lubricants can be derived from temperature/viscosity data.

The authors are to be congratulated for another fine contribution.

Additional References

13 Harrison, G., *The Dynamic Properties of Supercooled Liquids*, Academic Press, London 1976, p. 174.

14 Hedvig, Peter, *Dielectric Spectroscopy of Polymers*, Halsted Press, Division of John Wiley & Sons, Inc. New York, 1977, p. 196.

15 Stearns, R. S., et al., *Ind. Eng. Chem. Prod. Res. Develop.*, Vol. 5 No. 4, 1966, pp. 306-313.

Authors' Closure

In response to Dr. Lauer's question, we did obtain data on N1 similar to that shown for 5P4E in Figs. 5 and 6 of this paper. The transitions for N1, although clearly defined and similar to 5P4E, did not have as large a change in magnitude through the transition. The N1 used for the measurements was in the as received condition. No measurements were made on used samples.

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