The Science and Technology Behind the Measurement of Lubricants at High Temperature and High Shear

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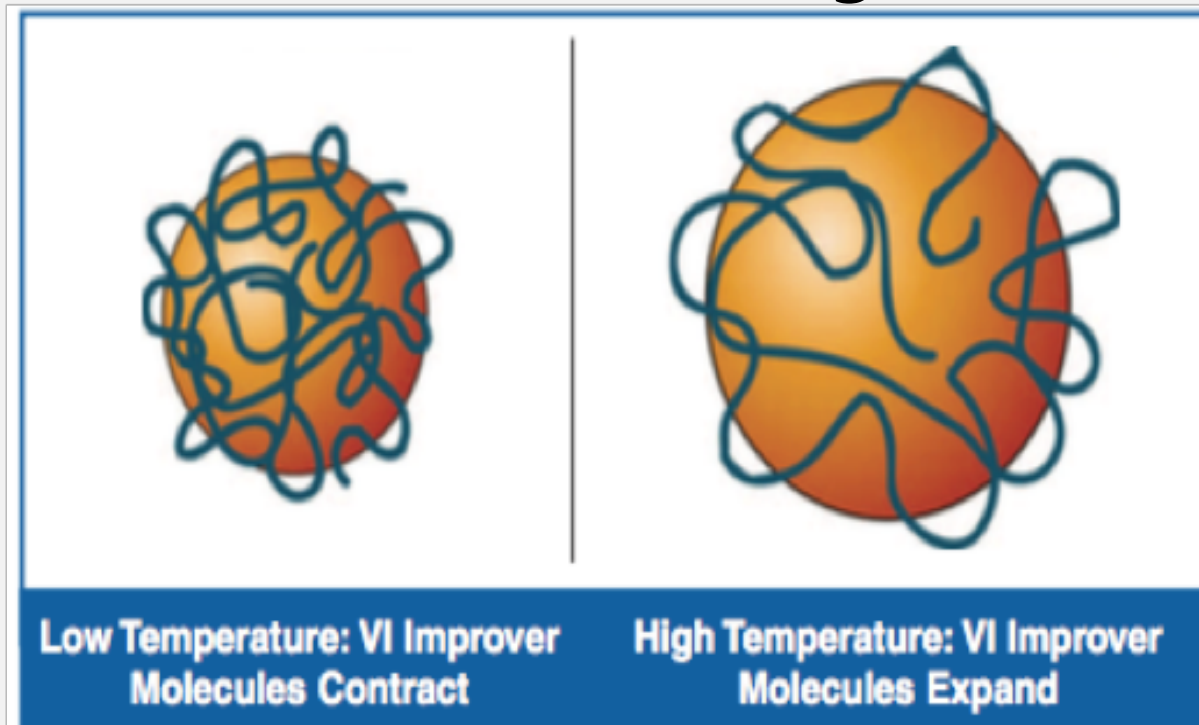Koehler Instrument Company, 85 Corporate Drive, Holtsville NY 11742

Overview

Viscosity is a critical property of engine lubricants that can greatly affect the performance and durability of the engine. During normal operating conditions, engine lubricants are subjected to high temperatures and high shear rates (HTHS) at critical lubrication areas such as the main journal bearings and piston ring cylinder wall. The HTHS viscosities of these engine lubricants are lower than the standard measured values using the ASTM D445 – Test Method of Kinematic Viscosity of Transparent and Opaque Liquids. Multigrade engine lubricants or oils are thickened with polymeric viscosity modifiers that combine low viscosity for cold starts and sufficiently high viscosity for normal operating temperature.

VI Improvers & DI Packages

At engine operating conditions, the viscosity of multigrade lubricants can decrease due to either or combination of high temperature and high shear rates. The use of polymeric viscosity modifiers changes the Viscosity Index (VI) of engine oils. VI improvers cause the lubricants to have a viscosity two to three times higher than mineral oils and also serves to increase fuel efficiency and improve pumpability during startups in low temperatures. There are two main types of VI improvers: dispersant, which assist in controlling deposits to prolong the life of engines and non-dispersant, which focus only on decreasing the viscosity's dependence on temperature. The VI improvers are inactive at low temperatures but activate at high temperatures to increase viscosity. Modern lubricants are also formulated with additives such as ashless dispersants and metallic detergents to control deposits, and other additives that has functions such as reducing oxidation, controlling wear and rust, and reducing friction. These additives are mixed in with diluent oil and are commercially available as Detergent – Inhibitor (DI) packages.

Low Temperature: VI Improver Molecules Contract | High Temperature: VI Improver Molecules Expand

Temperature and Shear Effects

Due to the additives and oil-soluble polymers, the lubricants display non-Newtonian characteristics. Unlike mineral oils, whose viscosities are strongly dependent on temperature and pressure, a fully formulated engine lubricant is dependent on all three variables of temperature, pressure and shear rate. When the shear rate is low, the viscosity stays constant. However, the viscosity starts to decrease as the shear rate increases, until a critical shear rate is reached. The viscosity beyond this critical shear rate will remain constant even with increasing shear rate. This decrease in viscosity is temporary and reversible if the lubricant polymers do no degrade. Even with the decreased viscosity at high shear rates, it is still higher than mineral/base oils without the oil-soluble polymers, making polymer formulated lubricants much more desirable. A similar situation occurs at high temperatures. An increase in temperature will result in a lower viscosity due to the increased oxidation, or the chemical aging of the lubricants. Conversely, lowering the temperature will cause an increase in viscosity and the life of the lubricants.
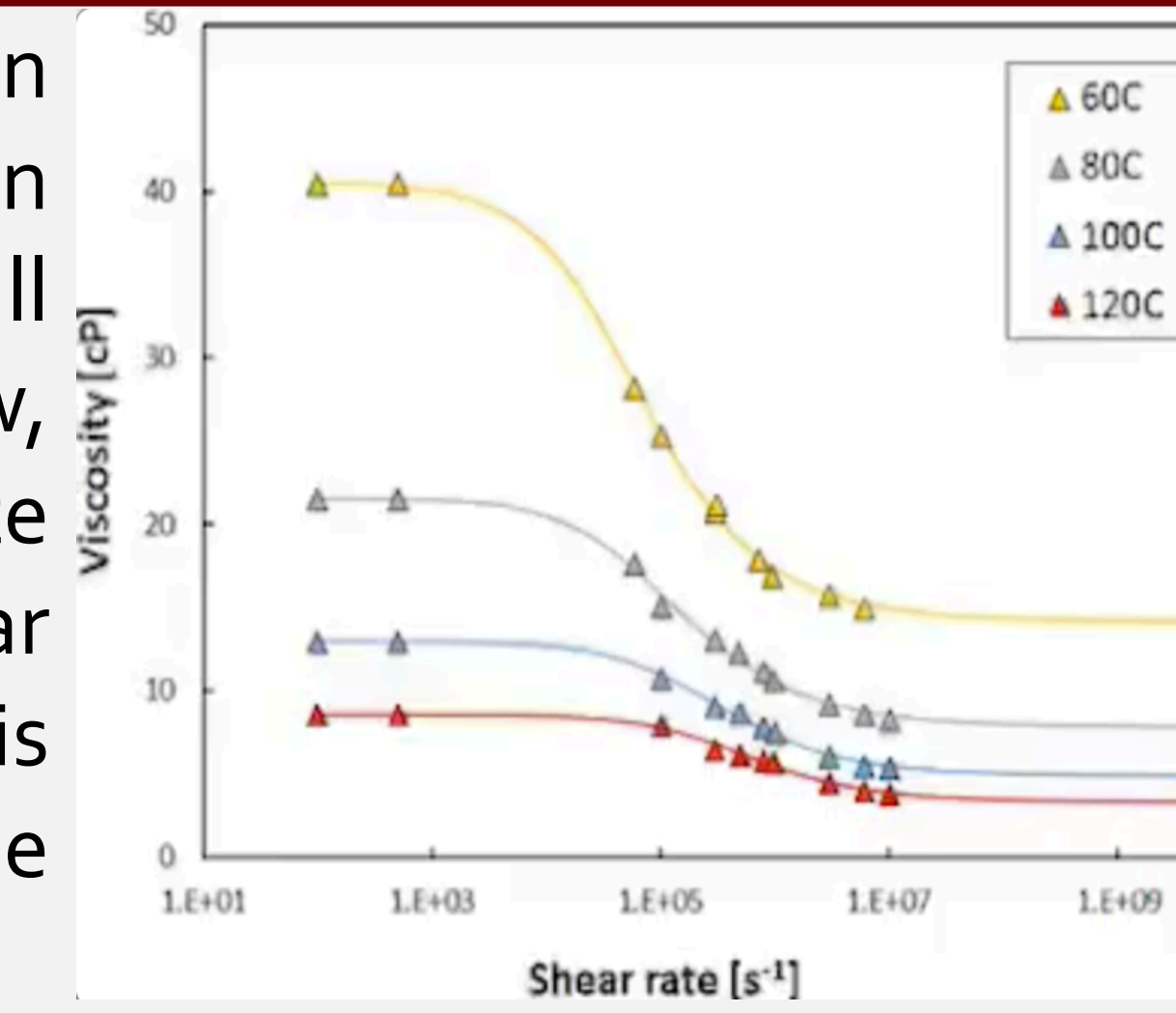
Pressure Drop Within the Capillary

The capillary viscometer is easy to construct, and it can also easily produce data on the flow rate for a specific shear rate for a lubricant. Despite this, certain perturbations such as the entrance and exit flow disturbances need to be accounted for. The total pressure drop across the capillary needs to include the entrance pressure drop and the pressure drop for the fully developed flow in the capillary. When the lubricant enters the capillary, it experiences a sudden contraction under steady flow, which is different compared to the fully developed flow region in the capillary.

$$\Delta P_{ent} = \rho U_0^2 \left(k + \frac{k'}{Re}\right)$$

As a result, the following equation is developed for the pressure drop at the entrance. It was found that the value for k' can fluctuate greatly based on the range of the Reynolds number, and studies at low Reynolds number determined the ratio of the observed gauge pressure drop to the pressure drop in the capillary is

$$\frac{\Delta P_{obs}}{\Delta P} = 1 + \frac{R}{L} \frac{Re * k + k'}{16}$$

Based on this equation, the difference in the pressure drops are negligible when $\frac{L}{R} > 200$ and $Re < 100$ since the ratios will be close to one. However, in order to have a fully developed flow in the capillary, the length of the capillary must be longer than the sum of the exit and entrance lengths. Finally, the previous equation was rearranged using experimental constants and it can be plotted to assist in creating the proper L/R ratio for the capillary.

$$\frac{\pi R^4}{\rho Q^2} \Delta P_{obs} = k + \frac{8\mu}{\rho} \frac{Rk'}{16}$$

Viscous Heating within the Capillary

Another important correction is associated with the viscous heating arising from shear close to the capillary wall. This is considered non-uniform and the highest temperature rise is at the part where the shear rate is the highest. This issue was addressed and solved by Gerrard et al. They assumed that the velocity profile at the entrance is parabolic and they found that the profile at the exit flattened out due to the viscous heating. They also made theoretical calculations that matched up with experimental data. Several experiments were done for multiple fluids in order to determine correction curve for pressure and viscous heating, but it is only limited to capillary devices and extrapolative approaches are inconvenient with this method.
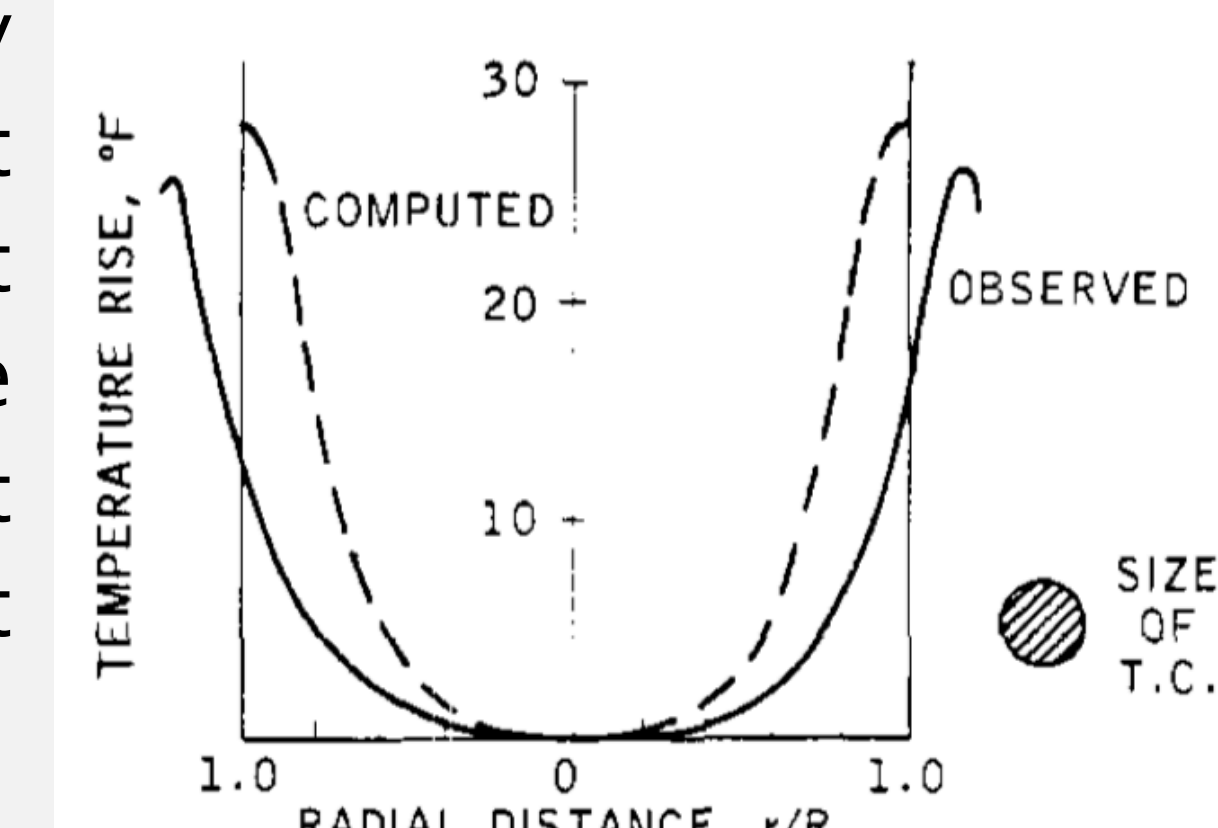
Data Comparison

HTHS viscosity data was collected using a capillary viscometer for various HT lubricant standards compared to their known HTHS viscosities. Corrections for fully developed capillary design and flow were incorporated into these measurements. The values obtained from the HTHS capillary viscometer are quite close (< 2% overall difference) to the reported HTHS viscosities. The overall conclusion from this study show that the capillary viscometer used in this study, can measure HTHS viscosities of engine lubricants.

	ASTM HTHS Classification		HT39	HT75	HT150	HT240
	Pressure for Test (psi)		225	290	375	480
Known Data	Density $\left(\frac{g}{mL}\right)$		0.7871	0.7891	0.7938	0.7984
	Viscosity $(mPa*s)$		2.096	2.832	3.549	4.702
Test Data	Trials	Viscosity $(mPa*s)$ 1	2.1541	2.8091	3.5509	4.595
		2	2.0434	2.8109	3.5194	4.7217
		3	2.106	2.8052	3.5149	4.6788
		Shear rate $(*10^6 \ s^{-1})$ 1	1.31	1.318	1.391	1.396
		2	1.318	1.316	1.367	1.382
		3	1.304	1.312	1.37	1.383
	Avg. Viscosity from Test $(mPa*s)$		2.13	2.807	3.533	4.637
	Viscosity Difference, %		1.62	0.877	0.454	1.385

Conclusion

Keeping engine lubricants operable at high temperatures and high shears requires innovations such as VI improvers and DI packages. Furthermore, understandings of parameter effects, resulting from conditions of both the instrument and the testing environment, requires an in-depth analysis to ensure not only data reproducibility but also data accuracy. This is so that engine lubricants can withstand the actual working conditions of an engine and to provide the testing data that can guarantee its usability.

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