

# VISCOSITY MEASUREMENT AT HIGH TEMPERATURE AND VARYING SHEAR RATES FOR ENGINE LUBRICANTS

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.

These multigrade engine oils do exhibit temporary viscosity loss due to shear thinning and high temperatures. As a result of these operating conditions, several test methods have been ratified by the industry for HTHS measurements of engine oils;

ASTM D4683 – Standard Test Method for Measuring Viscosity of New & Used Engine Oils at HTHS by Tapered Bearing Simulator Viscometer at 1500°C.

ASTM D4741 – Standard Test Method for Measuring Viscosity at HTHS by Tapered Plug Viscometer.

ASTM D5481 – Standard Method for Measuring Apparent Viscosity at HTHS Rate by Multicell Capillary Viscometer.

This paper highlights the theory of measuring viscosity using a capillary viscometer. We will focus on the design and provide recommendations for proper measurements and corrections in using a capillary viscometer suitable for HTHS viscosity measurements. Several HTHS viscosity standards oils were tested against these corrections and are tabulated for comparison.

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 improves cause the lubricants to have a viscosity two to three times higher than mineral oils. In addition to VI improvers, 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 [1].

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 not 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 [1].

It is imperative that viscosity measurements tests on engine lubricants be done under conditions as close to actual operating conditions as possible in order to properly assess a lubricant's performance. When engine lubricants are tested under high temperature and high shear conditions, it is found that the results more closely resemble data from engine friction measurements. It is also reported that high pressure high shear viscosities showed a better correlation with actual viscosity data when compared with low temperature high shear viscosities [13]. Therefore, high pressure also plays a role in determining the viscosity of lubricants at high shear rates.

As discussed previously, engine lubricants are made of polymers, which increase the viscosity of the oil much more at higher temperatures than at lower temperatures. Due to this, the oils aren't as dependent on temperature, by increasing the Viscosity Index, which leads to the name VI improvers. The VI improvers have other functions such as to increase fuel efficiency and improving pumpability during startups in low temperatures. There are two main types of VI improvers: dispersant and non-dispersant types. Non-dispersant VI improvers focus only on decreasing the viscosity's dependence on temperature, while dispersant types also assist in controlling deposits to prolong the life of engines [1]. Not only is it vital to understand the parameters that affect

the viscosity of engine lubricants, it is also essential to have a viscometer that can measure engine oil viscosities at conditions that will provide results close to engine operating conditions. 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, and viscous heating in the capillary 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 [1]. As a result, the following equation is developed for the pressure drop at the entrance [14].

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

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 [15]:

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

Based on this equation, the difference in the pressure drops are negligible when

$$\frac{L}{R} > 200 \quad \text{and} \quad Re < 100$$

since the ratios will be close to one [1]. 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 [1,16]. Finally, the previous equation was rearranged using experimental constants and was obtained to be [1]:

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

This equation can be plotted to determine the R and k values from the slope, which will assist in creating the proper L/R ratio for 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 [1]. This issue was addressed and solved by Gerrard et al. [17, 18]. 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 [1].

In Table 1, 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.

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Table 1: HTHS Viscosity Comparisons of Calibration Oils at 150°C

ASTM HTHS Classification		HT39	HT75	HT150	HT240		
Known Data	Pressure for Test (psi)	225	290	375	480		
	Density ( $\frac{g}{mL}$ )	0.7871	0.7891	0.7938	0.7984		
	Viscosity ( $mPa \cdot s$ )	2.096	2.832	3.549	4.702		
Test Data	Trials	Viscosity ( $mPa \cdot s$ )	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 ( $mPa \cdot s$ )		2.13	2.807	3.533	4.637		
Viscosity Difference, %		1.62	0.877	0.454	1.385		

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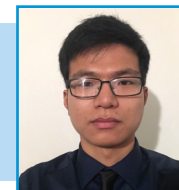
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