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High Shear Rate Rheology of Lower Viscosity Engine Oils Over a Temperature Range of 80° to 150°C Using the Tapered Bearing Simulator (TBS) Viscometer

2010-01-2288
Published
10/25/2010

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ABSTRACT

In 2005, the growing emphasis on fuel efficiency coupled with the long-recognized negative effects of viscous friction caused by engine hydrodynamic lubrication, led to considerations of the benefits of lower viscosity engine oils by the SAE Engine Oil Viscosity Classification (EOVC) Task Force. More recently, these considerations were given further impetus by OEM enquiry regarding modification of the SAE Viscosity Classification System to include oils of lower viscosity specification than that of SAE 20.

For the EOVC Task Force, such considerations of commercially available, significantly lower viscosity engine oils, also produced a need to reassess the precision of high shear rate viscometry of such engine oils as presently practiced at 150°C - as well as interest in temperatures such as 100° and 120°C believed more representative of engine operating conditions.

This paper presents studies of the precision of high shear rate viscometry on lower-viscosity simulated engine oils at temperatures of 80°, 100°, 120°, and 150°C at a shear rate of one million reciprocal seconds ($1.0 \cdot 10^{6}\ s^{-1}$) using the Tapered Bearing Simulator (TBS) Viscometer. These viscosity values were then analyzed for conformity to the MacCoull, Walther, Wright viscosity-temperature and the ability to interpolate high-shear rate viscosities. Lastly, the ability to determine the high shear rate viscosities of oils at various chosen temperatures was applied in appraising the fuel efficiency benefits of such oils by determining the Viscous Fuel Efficiency Index. These values are, in turn, compared both to one another and to the Index values of several hundred North American engine oils collected by the Institute of Materials in 2008 and 2009 for their yearly engine oil database.

INTRODUCTION

VISCOSITY AND ENGINE PROTECTION

Engine durability and the viscosity of the engine oil are inextricably bound. This is because the viscosity level determines the effectiveness of the engine oil's primary function in protecting the engine from wear through the process of hydrodynamic lubrication. The latter process depends upon the oil's inability to flow rapidly enough to escape the applied high pressure area between two surfaces in relative motion. That is, the higher the viscosity, the less readily the oil can escape and thus the relatively incompressible oil film must separate the surfaces which would otherwise wear against one another.

VISCOSITY AND ENERGY ABSORPTION

However, the viscosity of oil is actually a measure of its internal molecular friction and, as a form of friction, hydrodynamic lubrication comes at the price of engine energy loss - the higher the viscosity the greater the energy loss. Thus, selection of engine oil viscosity should be that level giving 1) engine durability and 2) operating efficiency. Obviously, durability must be placed foremost or efficiency would be quickly lost to deleterious and costly mechanical friction and, ultimately, engine failure.

HIGH SHEAR RATE VISCOMETRY

THE ENGINE AND HIGH SHEAR RATE VISCOMETRY

BACKGROUND

On the basis of lubricant formulation experience gained in the early 1940s, viscosity modifiers (VMs) were introduced to improve engine startability at low temperatures. These VM additives also introduced engine oils that were no longer Newtonian in behavior [1] and, therefore, whose viscometric responses to engine operation were no longer easily predictable from previous experience with Newtonian fluids.

Over a number of years, concerns initially expressed regarding this new class of 'multigrade'[1] engine oils regarding rheological phenomena of so-called 'temporary' and 'permanent' viscosity losses were resolved by experience and much technical dialogue. In the process, it was recognized that measuring engine oil viscosity at low shear rates (as had been the practice over many preceding years) gave insufficient understanding of the oil's viscometric function in the engine. Consequently, much new development was required to produce viscometry at the higher shear rates simulative of engine hydrodynamic lubrication. Several approaches were investigated and by the 1980s two viscometric approaches capable of operating at higher temperatures and shear rates [2, 3] and three instruments were available for the development of associated ASTM Test Methods [4, 5, 6].

In 1989, high shear rate viscometric data led to a seminal paper by Spearot [7], given in a symposium on the subject of the relationship of high shear rate viscometry and engine bearing response [8]. This, in turn, led to the inclusion of high shear rate viscometry in the SAE's Engine Oil Viscosity Classification System, J300. Important parameters of 1) a shear rate of $1.0 \cdot 10^6 s^{-1}$ at 2) 150°C were chosen as reasonably representative of engine operational conditions of relevance. Accordingly, new high shear rate values representing the SAE Grades operative at the time were established and incorporated in the SAE EOVC Classification System. Since that time, studies in understanding polymer response have pushed engine oil viscometry into a wide range of shear rates and temperatures [9].

RECENT CHALLENGES TO THE MEASUREMENT OF ENGINE OIL VISCOSITY

In these and future times, fuel efficiency of the automotive engine is, and will be, of high importance to all aspects of modern automotive transportation in developed and developing areas of the world. Governments are mandating significant improvements in fuel efficiency from OEMs. This has already led to a number of responses such as hybrid engines; very small, low-power passenger cars; completely electric-powered vehicles; and a number of changes in the design of modern fueled engines.

As a consequence of this reach for fuel efficiency, the energy-absorbing effect of engine oil viscosity previously mentioned came to the fore. Reduction of operating viscosities of engine oils to considerably lower levels than those presently available was proactively proposed [10] in 2005 by the Chair of the SAE Engine Oil Viscosity Classification Task Force as a desirable direction for the SAE Classification System. Recently, they received requests from OEMs for addition of engine oils to the SAE EOVC System with high-temperature/high-shear-rate (HTHS) viscosities as low as 1.7 mPa•s at 150°C [11].

In discussing this request, the EOVC Task Force considered the fact that the proposed viscosity level was considerably below a viscosity level that in the early 1990s was reported to mark the point (about 2.4 mPa•s) at which some engines would begin to show abnormal engine wear response [12,13]. However the EOVC Task Force weighed 1) its own proactivity concerning the effect of lower engine oil viscosity on fuel efficiency, 2) the fact that the request was associated with OEM interests and 3) that engine design has changed markedly over the last decade, and agreed that it should consider adding viscosity classifications lower than SAE 20.

Since such low viscosity levels were relatively unstudied at high shear rates, one of the first questions was whether the precision levels of the high shear viscometers referenced in SAE J300 which were developed around higher viscosity levels, would remain acceptable [14]. Consequently, eleven simulated engine oils having HTHS viscosities in the range of OEM interest were made of Group III base oils containing VMs to allow determination of both their high and low shear rate viscometric characteristics [15].

To meet the need expressed to estimate potential high shear rate precision, the author offered to analyze samples of these oils in his laboratory at $1.0 \cdot 10^6 s^{-1}$ shear rate and 150°C using the TBS Viscometer. He also thought it might be of additional value to measure the oils at lower temperatures [15] should temperatures closer to engine operation in short-trip driving become of interest. This initial work was reported to the Task Force in December 2009 [16] including the studies of these oils at both 100° and 80°C, also at a shear rate of $1.0 \cdot 10^6 s^{-1}$. In addition, this work provided the initial

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[1] So named because they span several viscosity requirements or 'Grades' of the SAE's EOVC System, J300.

basis of the more extensive rheological studies of viscosity and its role in fuel efficiency discussed in this paper.

All of the high shear rate viscometric studies reported in this paper were performed on the TBS Viscometer.

HIGH SHEAR RATE STUDIES

BACKGROUND

The TBS Viscometer was brought into laboratory use in 1980 [2] and accepted as ASTM Test Method D4683 in 1987 with round-robin 0.96% repeatability. Very recently, in another ASTM round robin including both fresh and used engine oils, the previous repeatability was confirmed with a value of 1.04% [17]. In both manual and automated calibration and application, the viscometer differs from other instruments in being an absolute viscometer. That is, shear stress and shear rate can be measured directly - the later by reciprocal torque and rotor height measurements using any Newtonian fluid [18].

The present form of the instrument is shown in Figure 1. Absolute viscometry is applied to establish the viscosity of the non-Newtonian reference oil at any chosen shear rate. Such non-Newtonian reference oils are then used to automatically or manually check and, if needed, adjust rotor position during operation. All the viscometric data in this paper were obtained at shear rates of $1.0 \bullet 10^{6} s^{-1}$.

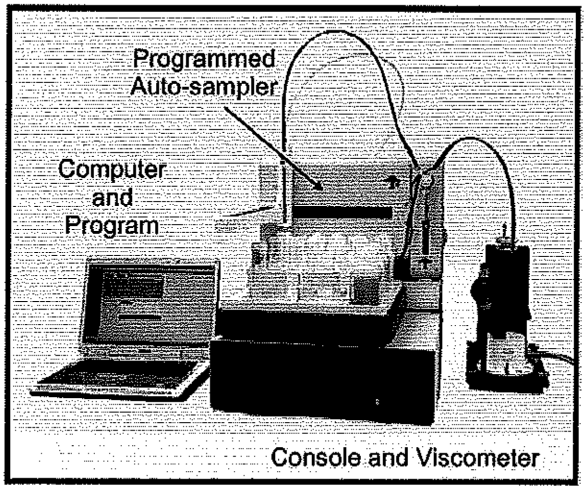

Fig. 1. The Tapered Bearing Simulator Viscometer and supporting equipment for fully automatic operation.

APPLICATION TO LOW-VISCOSITY SIMULATED ENGINE OILS

As mentioned, to initially address the question of viscometric precision for the EOVC Task Force, the instrument was applied to a set of eleven low-viscosity, simulated engine oils provided [15]. Results are given in Figure 2. This data, showed that the range of viscosities of these eleven oils was from 1.9 to 2.6 mPa•s and replicate viscosities for the eleven oils averaged 0.010 mPa•s.

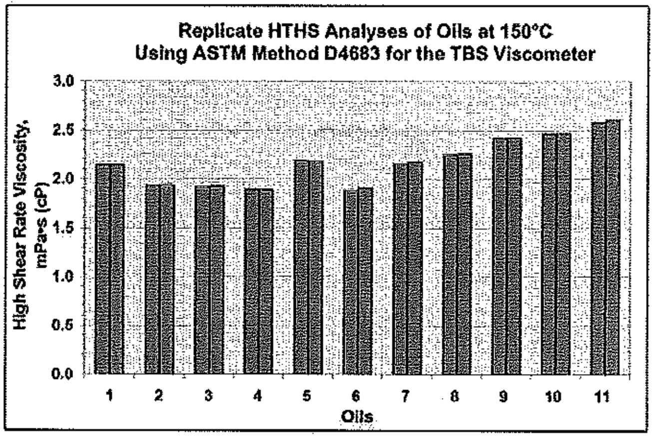

Fig. 2. Precision of replicate determinations of high shear rate viscosities of eleven simulated low viscosity engine oils.

As mentioned earlier, availability of these low-viscosity oils for work at 150°C also provided the opportunity to evaluate the precision possible at lower temperatures. For this purpose, the viscometer was applied at $1.0 \bullet 10^{6} s^{-1}$ and at 80° and 100°C. These results combined with results given in Figure 2 are shown in Figure 3. In this viscometric study, the fully automated capability of the viscometer at these two temperatures was used. However, at 80°C the absolute technique for positioning the rotor to obtain $1.0 \bullet 10^{6} s^{-1}$ shear rate was used with manual injection of the eleven oils.

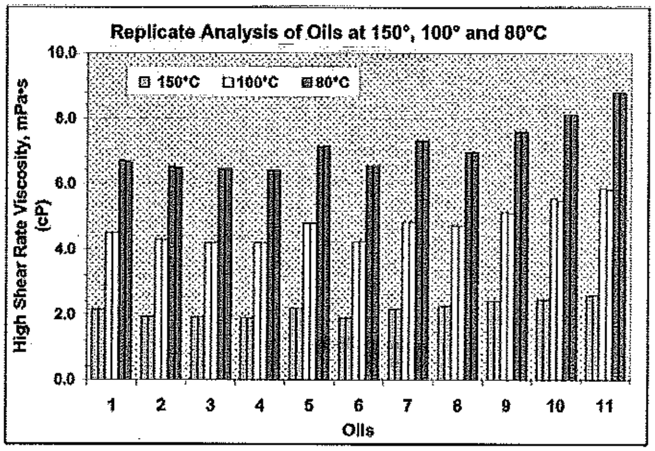

Fig. 3. Precision of replicate determinations of high shear rate viscosities of eleven simulated low viscosity engine oils at 150°, 100° and 80°C.

Table 1 shows variation in the viscosities of these eleven oils at the three temperatures. Average replication values and their percent of the average viscosities of the eleven oils give a view of relative precision at the three temperatures. All of the latter values are less than 1%. Such replication of the viscometric data at all three temperatures seemed encouraging in regard to the initial SAE EOVC question of viscometric precision at a shear rate of $1.0 \cdot 10^6 s^{-1}$ particularly considering this heretofore untested viscosity range of proposed low-viscosity engine oils.

Table 1. Precision Study of Eleven Simulated Low-Viscosity Engine Oils Using the TBS Viscometer at Temperatures of 150°, 100° and 80°C

Temperature, Celsius	Viscosity Range, centiPoise, mPa•s		Repeatability, avg. mPa•s	Percent of Average Viscosity
150	1.89	2.61	0.010	0.46
100	4.18	5.79	0.022	0.46
80	6.40	8.78	0.014	0.20

MWW VISCOSITY-TEMPERATURE RELATIONSHIP

Having viscosities of the eleven simulated engine oils at three temperatures, on the basis of earlier work [9], it was of further interest to see if the viscometric data gathered at the three temperatures and high shear rates would produce linear plots using the empirical MacCoull, Walther, Wright (MWW) equation [19, 20, 21] that has been widely applied in low shear rate, capillary viscometry since the early 1920s.

Using natural logarithms, the equation can be expressed as:

$$\text{Ln Ln (Viscosity} + 0.7) = \text{(Ln Kelvin)} \cdot \text{slope} + \text{intercept} \qquad (1)$$

Figures 4, 5 and 6 show the MWW data for these eleven oils. Although more limited in selected temperatures, these linear plots support the previous work reported [9] that contained more extensive data. As will be shown later in this paper, the MWW approach has value in determination of high shear rate values at other temperatures.

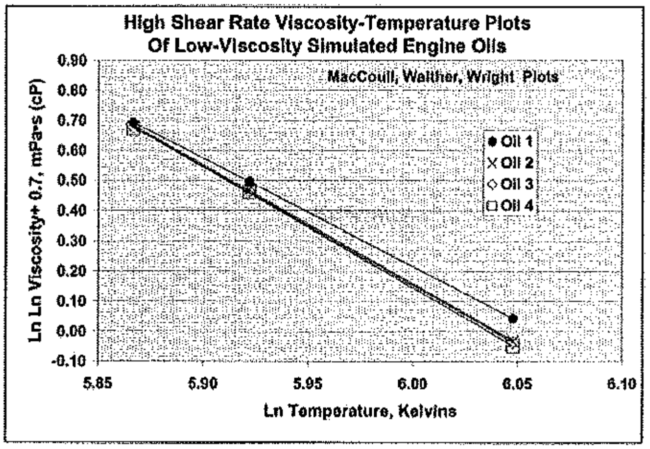

Fig. 4. Application of MWW equation to Simulated Engine Oils 1 through 4.

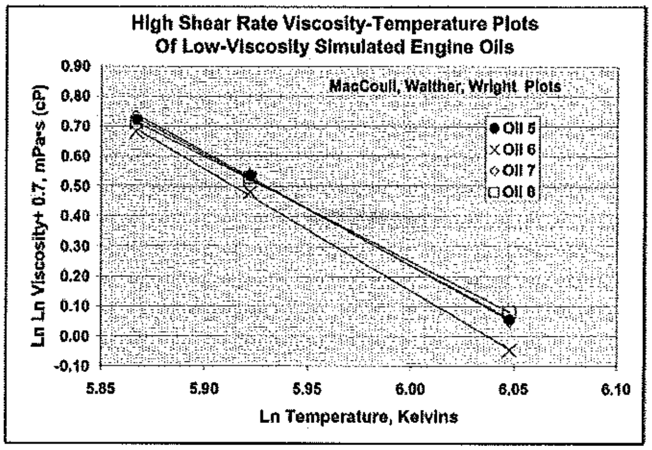

Fig. 5. Application of MWW equation to Simulated Engine Oils 5 through 8.

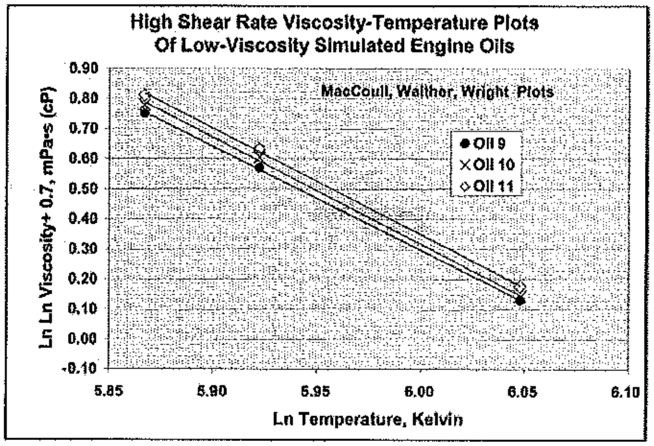

Fig. 6. Application of MWW equation to Simulated Engine Oils 9 through 11.

SECOND SET OF LOW-VISCOSITY SIMULATED ENGINE OILS

The replication data on the initial eleven oils at high shear rates encouraged an EOVC Low Viscosity Task Group and a second set of twelve low-viscosity, simulated engine oils were made available from the previous source [15, 22]. Eleven of these were re-blends of the first set and a twelfth was added to round out the range of viscosities desired. These re-blended oils were made in sufficient quantity to support an anticipated ASTM round robin of all three HTHS instruments used in SAE J300. The twelve oils also provided a further opportunity to evaluate their high shear rate viscosities over a temperature range and to determine their potential contribution to improvement in fuel efficiency.

In addition to the three temperatures previously applied, and considering potential interest in another temperature in the upper operating range of engine oils, the high shear rate viscosities of these simulated engine oils were also measured at 120°C.

Results of replicate measurements of viscosities at the temperatures of 80°, 100°, 120° and 150°C are shown in Table 2 and Figure 7.

Table 2. TBS Viscometric Analyses of Low Viscosity Oil Set at Temperatures of 80°, 100°, 120° and 150°C

Oil Number	Viscosity @ 80°C		Viscosity @ 100°C		Viscosity @ 120°C		Viscosity @ 150°C	
	Run 1 mPa•s	Run 2 mPa•s	Run 1 mPa•s	Run 2 mPa•s	Run 1 mPa•s	Run 2 mPa•s	Run 1 mPa•s	Run 2 mPa•s
1	6.63	6.66	4.48	4.52	3.37	3.35	2.23	2.20
2	6.40	6.39	4.27	4.28	3.09	3.10	2.00	1.98
3	6.42	6.42	4.31	4.34	3.12	3.13	1.98	1.99
4	6.32	6.33	4.30	4.33	3.11	3.11	1.97	1.96
5	7.03	7.02	4.94	4.96	3.58	3.61	2.26	2.26
6	6.50	6.52	4.33	4.30	3.08	3.10	1.98	2.00
7	7.17	7.18	4.82	4.81	3.51	3.51	2.25	2.24
8	6.91	6.93	4.77	4.78	3.62	3.62	2.38	2.37
9	7.59	7.61	5.20	5.20	3.86	3.85	2.51	2.51
10	8.16	8.15	5.77	5.79	4.10	4.10	2.59	2.59
11	8.61	8.60	5.84	5.89	4.16	4.16	2.67	2.66
12	6.08	6.09	3.97	3.98	2.87	2.87	1.86	1.85

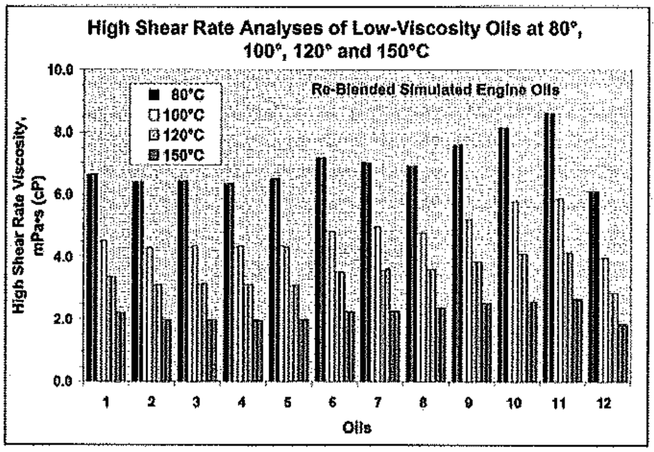

Fig. 7. Replicate analyses of twelve simulated low-viscosity engine oils at temperatures of 80°, 100°, 120° and 150°C.

Table 3. Low-viscosity study at temperatures of 150°, 120°, 100° and 80° C.

Temperature, Celsius	Viscosity Range, centiPoise, mPa•s		Repeatability, avg. mPa•s	Percent of Average Viscosity
150	1.85	2.67	0.0108	0.971
120	2.87	4.16	0.0083	0.480
100	3.97	5.89	0.0217	0.906
80	6.08	8.61	0.0134	0.382

Table 3 repeats information in Table 1 for the new set of twelve simulated engine oils at each temperature. Data for viscosities at both 80° and 120°C were obtained using the manual absolute technique. Again, the percent variation in replication of viscosity at all levels is below 1% of the average viscosity for the twelve oils.

EXTENDED MWW VISCOSITY-TEMPERATURE ANALYSIS

The high shear rate data obtained at four temperatures shown in the previous section of the paper were again analyzed for conformity to the MacCoull, Walther, and Wright (MWW) equation. Figures 8, 9, 10 show the linearity of the data for the twelve oils. In this set of analyses using the MWW equation, the data from the four temperatures were expected to give a more dependable measure of linearity and when the values of the Coefficient of Determination, R^2, were determined, they ranged from 0.996 to 0.9993 showing that the MWW equation is useful in providing a linear fit of the data over the 80° to 150°C temperature range.

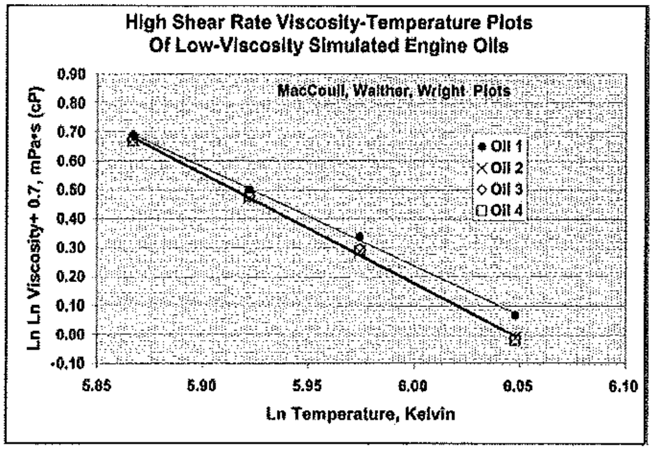

Fig. 8. Application of MWW equation to re-blended low-viscosity Simulated Engine Oils 1-4.

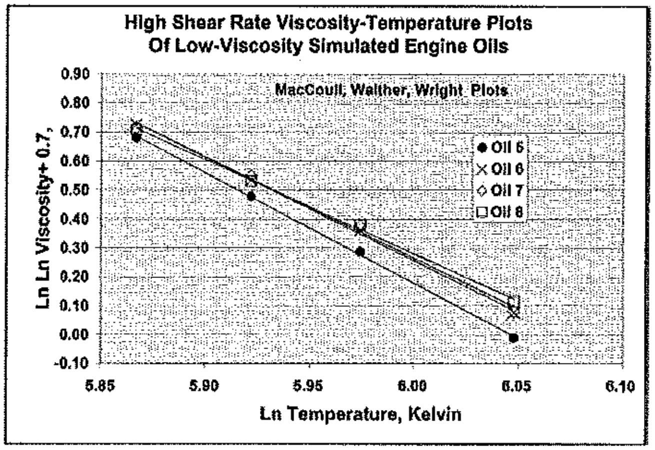

Fig. 9. Application of MWW equation to re-blended low-viscosity Simulated Engine Oils 5-8.

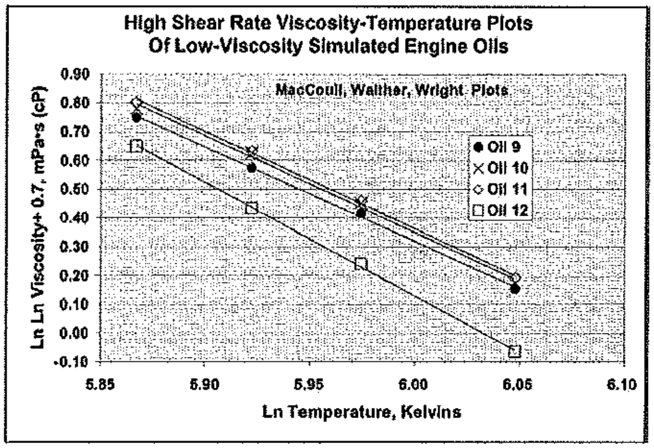

Fig. 10. Application of MWW equation to re-blended low-viscosity Simulated Engine Oils 9-12.

APPLICATION OF HIGH SHEAR RATE MWW EQUATION TO INTERPOLATE VISCOSITIRS AT OTHER TEMPERATURES

Using the data from the MWW equations generating Figures 8, 9, 10, the high shear rate viscosities at 120°C were calculated by interpolation from the high shear rate values determined at only the temperatures of 150°, 100°, and 80°C. These calculated values were then compared to the viscosities actually determined at 120°C. Figure 11 shows this comparison.

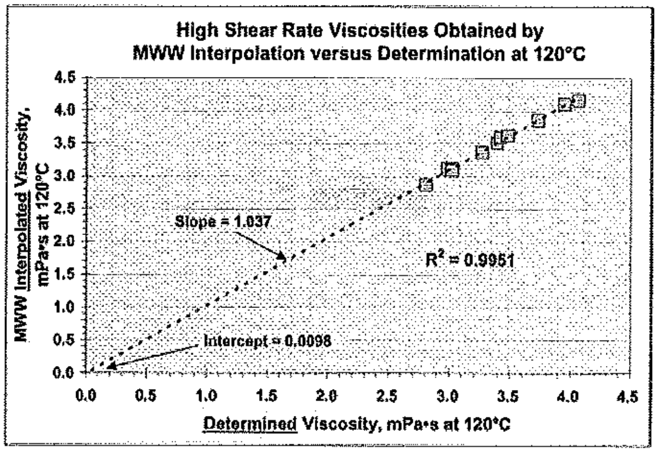

Fig. 11. Correlation of interpolated and determined high shear rate viscosities of 12 low-viscosity simulated engine oils.

Correlation of the interpolated and determined viscosity data shows a slope of 1.04 mPa•s/mPa•s, and an intercept of 0.01 mPa•s. The value of the Coefficient of Determination, R^2, is 0.995. Thus, interpolation, and likely some degree of extrapolation of high shear rate viscosity is reasonable using the MWW equation with high shear rate data.

VISCOMETRY, TEMPERATURE, MWW AND FUEL EFFICIENCY

The viscosity levels and slope values of the linear MWW curves in these multi-temperature, high shear rate viscosity data have an interesting significance when used to generate the calculated Viscous Fuel Efficiency Index (V-FEI) [23] with its implications regarding viscous losses on fuel efficiency. Discussion regarding the significance of viscosity at lower temperatures on fuel efficiency led to an extension of the studies to investigate this basic area of importance [24].

Of course, viscous losses are only one of several significant forms of engine power loss including pumping losses, boundary friction losses, etc. However, viscous losses are perhaps the most readily reducible form of loss through the simple expedient of changing engine oil.

DETERMINATION OF V-FEI

The V-FEI is determined from the temperatures and energy losses in lubricating five areas of the engine responsible for essentially all of viscous friction effects [25]. The viscosity-related friction losses of these five areas, with their nominal operating temperatures [23], are shown in Figure 12

These energy loss percentages and temperatures are associated with one engine and would be expected to vary somewhat from engine to engine. However, any given set of values should permit reasonably invariant comparison of viscous energy losses of engine oils.

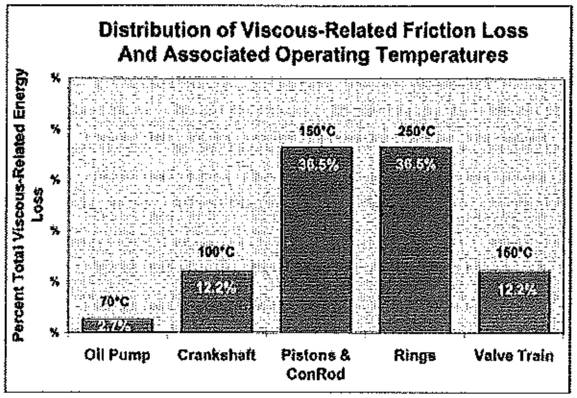

FIG. 12. Important areas and operating temperatures of the engine in which energy is lost by viscous friction.

To obtain the V-FEI value, it is necessary to sum the percent viscous energy loss of each of the five areas per unit viscosity at each particular area's temperature (that is, $\%VL_A / \eta_{°C}$ where VL_A is the viscous loss in the area and $\eta_{°C}$ is the viscosity of the engine oil at the temperature in the area). Accordingly, the lower the high shear rate operating viscosity in each of the five critical areas of the engine, the greater will be the relative fuel efficiency of an engine oil. It is assumed that the sum of viscous energy losses of these five areas is 100% of all viscous energy losses.

Thus, the equation developed for V-FEI is:

$$\begin{aligned} \textbf{V-FEI} = {} & (\%VL_{OP} / \eta_{70°C}) + (\%VL_{CS} / \eta_{100°C}) + \\ & (\%VL_{PC} / \eta_{150°C}) + (\%VL_{R} / \eta_{250°C}) + \\ & (\%VL_{VT} / \eta_{150°C}) = 100\% \ \textbf{V-FEI} \end{aligned} \qquad (2)$$

in which **OP** is **Oil Pump, CS** is **Crankshaft, PC** is **Piston and ConRod, R** is **Rings**, and **VT** is **Valve Train.**

Applying V-FEI to Low-Viscosity Simulated Engine Oils

Since improvement in fuel economy was the primary factor leading to consideration of low-viscosity engine oils, it was considered of significant interest to compare the V-FEI of the twelve simulated engine oils to one another. Results are shown in Figure 13 in which the V-FEI of the twelve low-viscosity, simulated engine oils are plotted against their viscosities at 150°C and $1.0 \cdot 10^6 s^{-1}$ shear rate. Over the decreasing range of viscosities from 2.60 to 1.85 mPa•s, V-FEI values increase from 56 to 76 in a power-law curve indicating exponential increase in V-FEI with decreasing viscosity. What effects, if any, lower viscosities would have on decreasing levels of hydrodynamic lubrication is presently uncertain.

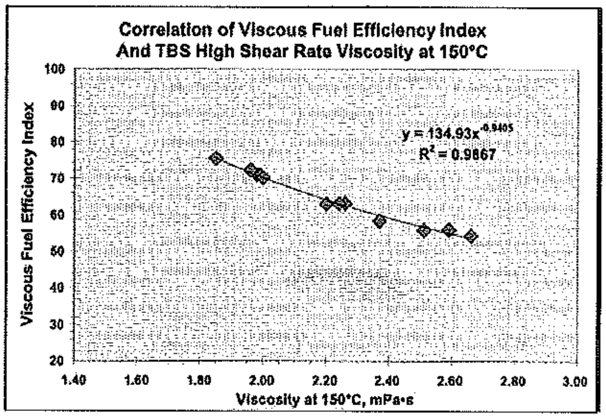

Fig. 13. Increase in the Viscous Fuel Efficiency Index with decreasing high shear rate viscosities at 150°C.

To gain further insight into the significance of these low-viscosity simulated engine oils in terms of comparative fuel efficiency benefits related to viscous loss, Figure 14 shows a comparison of the twelve simulated engine oils to 500 oils collected from the North American market during the years of 2008 and 2009. It is evident that the viscous fuel efficiency markedly exceeds all but very few of the oils collected.

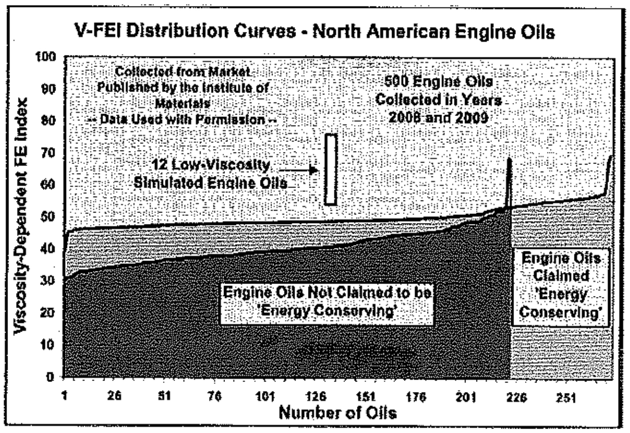

Figure 14. Viscous Fuel Efficiency Index of the twelve low-viscosity simulated engine oils compared to the range of present-day North American engine oils.

DISCUSSION AND SUMMARY

VISCOMETRY OF ENGINE OILS

PAST CHANGES IN THE PRACTICES OF VISCOMETRY

As noted earlier, the viscometry of engine oils has changed markedly over the last half-century. This transition was initially generated and accelerated by the introduction and rapidly growing use of viscosity modifiers (VMs) to improve the viscosity-temperature properties of engine oils. These oils - found to be non-Newtonian in character - introduced a new 'multi-grade' era of engine oils and, at the same time, the need to define their viscometric properties at shear rates simulating oil performance in the engine.

This was a fundamental change in viscometry - at both higher and lower temperatures - as the broad application of low-shear capillary viscometry gave way to viscometry at specified shear rates, particularly the shear rates much more representative of the higher temperature hydrodynamic lubrication occurring in operating engines. As a consequence, high shear rate values at 150°C became one of the critical criteria of engine oils in the viscometric classification of engine oils.

With broad application of HTHS engine oil viscometry established, more recently the EOVC Task Force has proactively led to consideration of another aspect of viscosity - its inherent viscous friction and related energy extraction from the operating engine. Since viscosity is an exponential function of temperature with its attendant effects on both energy absorption and hydrodynamic lubrication, it is evident that controlling both engine operating efficiency, as well as wear protection, are mutual considerations.

PRESENT ASPECTS OF VISCOMETRY: LOW-VISCOSITY ENGINE OILS

Concomitant with the EOVC Task Force's consideration of lower viscosity engine oils, recent evidence of the ability of OEMs to use such low-viscosity engine oils in automotive engines has been timely. A new range of viscosity classification extending down from the present lower limit of 2.6 mPa•s for an SAE 20 Grade to a new lower limit of 1.7 mPa•s is being considered. While, admittedly, the latter limit is well below some wear thresholds reported [12, 13] a decade or so previous, much has changed in engine design and fabrication and, presumably, those OEMs requesting these lower viscosity oils are quite knowledgeable of the responses of their engines.

Work reported to, and by, the SAE EOVC Task Force [26] show that all three HTHS viscometers presently used in SAE J300 classification (the Tapered Bearing Simulator Viscometer, the Tapered Plug Viscometer and the MultiCell Capillary Viscometer) indicate little or no loss in their relative precisions as indicated by replication of the high shear rate data on the low-viscosity simulated engine oils provided for test at a temperature of 150°C and shear rate of $1.0 \cdot 10^6 s^{-1}$ shear rate. In further support, ASTM has been requested and has agreed to obtain further information on the precision of these viscometers with simulated or actual oils of lower viscosities.

VISCOUS ENERGY ABSORPTION OF LOW-VISCOSITY ENGINE OILS

MACCOULL, WALTHER, WRIGHT INTERPOLATION

Using the absolute viscometry available with the TBS Viscometer, the viscosity-temperature relationships of these low-viscosity oils were studied at the temperatures of 150°, 120°, 100°, and 80°C. Precision at the three latter temperatures as indicated by two replicate analyses of each test oil were equivalent to that at 150°C. Moreover, it was shown that the empirical MacCoull, Walther, Wright (MWW) equation previously discussed, was also applicable to these collected data.

By applying the resulting linear MWW equations using the TBS data at 150°, 100°, and 80°C, calculating the viscosity at 120°C, and comparing these values with those actually obtained, the predicted viscosities were within a few tenths of a mPa•s of the determined values. This strongly suggests that interpolation of high shear rate data using the MWW equation is reasonably accurate and, with further experience, limited extrapolation of high shear rate data may also be found acceptable and helpful.

LOW-VISCOSITY EFFECTS ON FUEL EFFICIENCY

Using the Viscous Fuel Efficiency Index (V-FEI) (which compares different oils by their percent energy loss in five areas of the engine), the twelve low-viscosity simulated engine oils showed a systematic increase in V-FEI. That is, when their V-FEI values were plotted against their 150°C viscosities from 2.66 to 1.85 mPa•s, the systematic change in V-FEI was a segment of a power-law curve in which decreasing values of viscosity yield exponentially increasingly gains in V-FEI).

Comparing the values of V-FEI for the low-viscosity simulated engine oils comprising this study to the range of V-FEI values for all engine oils collected by the Institute of Materials over the years 2008 to 2009, Figure 14 indicates that the gain in fuel efficiency should be significant if other factors such as boundary lubrication and wear are controlled by engine design and/or additives.

It must be clearly noted that engine oil viscosity is only one of other important ways in which engine power is lost. However, viscous friction is a source of power loss that can be readily reduced by changing oil as long as there are no related deleterious effects on the engine.

SUMMARY

This multi-temperature, high shear study of simulated low-viscosity engine oils conducted with the Tapered Bearing Simulator Viscometer has shown several facets of the measurement and potential effects of low-viscosity engine oils:

1. The high shear rate viscosities of lower viscosity engine oils can be measured with essentially no presently evident loss of precision at several temperatures from 80° to 150°C. However, a planned ASTM Interlaboratory study on all three presently used high shear rate viscometers will confirm both precision and correlation.

2. Absolute viscometry at these high shear rates and several temperatures gave viscosities that closely fit the MacCoull, Walther, Wright empirical linear equation. This result provides the ability to interpolate (and perhaps extrapolate to some degree) high shear rate viscosities at other temperatures.

3. Comparative viscous friction losses in the areas of the engine most affected by such losses was made by determining the Viscous Fuel Efficiency Index. The benefit of reducing viscosity at high shear rates and 150°C was substantial and indicated that variation in the V-FEI obeys the Power Law. It would be of interest to examine several more modern engines for viscous friction losses and temperatures of importance in the areas of greatest viscous friction and to use this data to upgrade understanding of this source of engine power expenditure.

The overall results of the present high shear rate study suggests that the move to lower viscosity engine oils has much to recommend it but also requires application experience in various engine designs.

REFERENCES

1. Selby, T.W., **"The Non-Newtonian Characteristics of Lubricating Oils"**, *ASLE Transactions*, 1(1): 68-81, 1958.

2. Selby, T.W., Piasecki, D.A. and Smith, M.F., **"Development and Performance of the Tapered Bearing Simulator for High Shear, High Temperature Viscometry"**, 1981.

3. Manning, R.E. and Lloyd, W.A., "Multicell High Temperature High Shear Capillary Viscometer", SAE Technical Paper 861562, 1986, doi:10.4271/861562.

4. ASTM Standards, Test Method D4683; **"Measuring Viscosity at High Shear Rate and High Temperature by Tapered Bearing Simulator"**, Originally published in 1987 by ASTM Committee D02 on Petroleum Products and Lubricants, Subcommittee D02.07. Supporting data given in Research Report RR: D02-1211 available from ASTM Headquarters.

5. ASTM Standards, Test Method D4741; **"Measuring Viscosity at High Temperature and High Shear Rate by Tapered Plug Viscometer**, Originally published 1987 by ASTM Committee D02 on Petroleum Products and Lubricants, Subcommittee D02.07, Presently in Annual Book of ASTM Standards, **5**: 694-698, 2010.

6. ASTM Standards, Test Method D5481; **"Measuring Apparent Viscosity at High-Temperature and High-Shear Rate by Multicell Capillary Viscometer**, Originally published 1993 by ASTM Committee D02 on Petroleum Products and Lubricants, Subcommittee D02.07, Presently in Annual Book of ASTM Standards, **5**: 1177-1181, 2010.

7. Spearot, J.A., **"Relating High-Temperature, High-Shear-Rate Viscosity to Engine Operation"**, *ASTM Special Technical Publication 1068;* ASTM, Philadelphia, PA. 43-59, 1989.

8. High-Temperature, High-Shear Oil Viscosity Measurement and Relationship to Engine Operation, *ASTM STP 1068*, Spearot, J.A., Ed., ASTM, Philadelphia, PA, 1989.

9. Selby, T.W., "The Expanding Dimensions of High Shear Rate Viscometry," SAE Technical Paper 2008-01-1621, 2008, doi:10.4271/2008-01-1621.

10. Jackson, A., **SAE Fuels and Lubricants Council's Open Forum**, SAE Meeting and Exposition; Detroit, Michigan; April 12, 2005.

11. May, C., and Covitch, M., **Draft Minutes, EOVC Working Group Telecon on Viscosity Grades below SAE 20**, Aug. 19, 2009.

12. Demmin, R.A.; Girshick, F. and Schilowitz, A.M.; **"Engine Oil Viscosity and Bearing Wear: Field Test Results"**, *SAE Transactions*, **10**: 1820-1834, 1992.

13. Ohmori, T., Tohyama, M., Yamamoto, M., Akiyama, K., Tasaka, K. and Yoshihara, T., "Influence of Engine Oil Viscosity on Piston Ring and Cam Face Wear," SAE Technical Paper 932782, 1993, doi:10.4271/932782.

14. Draft Minutes, EOVC Working Group Telecon on Viscosity Grades below SAE 20, Aug. 19, 2009.

15. Draft **Minutes, EOVC Working Group Telecon on Viscosity Grades Below SAE 20**, Oct. 28, 2009.

16. Selby, T.W., **HTHS TBS Viscometer Studies on Lower Viscosity Engine Oils**, Presentation given at SAE EOVC Task Force Meeting, Dec. 9, 2009.

17. ASTM Test Method D4683: **Measuring Viscosity of New and Used Engine Oils at High Shear Rate and High**

Temperature by Tapered Bearing Simulator Viscometer at 150°C, Annual Book of ASTM Standards. **5**: 644-654, 2010.

18. Selby, T.W. and Piasecki, D., **"The Tapered Bearing Simulator - An Absolute Viscometer"**, 1983.

19. MacCoull, N., **Lubrication,** p.85, Texas Co., N.Y., NY, 1921.

20. Walther, C., **Erdöl und Teer,** 4: 510, 1928.

21. Wright, W.A., **"An Improved Viscosity-Temperature Chart for Hydrocarbons",** *Journal of Materials,* 4,(1): 19, 1969.

22. Goldmints, I., Maggi, C.P., Selby, T.S., Communications regarding re-blended low-viscosity oils preparation and availability, January 2010.

23. Selby, T.W., **"The Viscosity-Dependent Fuel Efficiency Index",** *Proceedings of the 13th International Colloquium Tribology - Lubricants, Materials, and Lubrication,* 2002.

24. Goldmints, I., Infineum USA L.P., personal communication, June 2, 2010.

25. Stone, R., **Introduction to Internal Combustion Engines, 2nd Edition,** McGraw-Hill, (1993).

26. May, C.M., Brown, M.G., Covitch, M.J., Goldmints, I., George, D.S. and Selby, T.W., "Extending SAE J300 to Viscosity Grades below SAE 20," 2010.

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ACKNOWLEDGEMENTS

The author would like to thank William Atkins of the Savant Laboratories for his dedicated and knowledgeable application of the Tapered Bearing Simulator Viscometer at the high shear rate and temperatures requested to form the information used for this paper. He would also like to express his appreciation for the opportunity to contribute further information on the high shear rate characteristics of low-viscosity, simulated engine oils kindly supplied to the author's laboratory by Isabella Goldmints of Infineum USA L.P. and the good offices of the SAE Engine Oil Viscosity Classification Task Force.

DEFINITIONS/ABBREVIATIONS

EOVC	Engine Oil Viscosity Classification
OEM	Original Equipment Manufacturer
HTHS	High-Temperature/High Shear
TBS	Tapered Bearing Simulator
VM	Viscosity Modifier
MWW	MacCoull, Walther, Wright
V-FEI	Viscous Fuel Efficiency Index

ISSN 0148-7191

doi:10.4271/2010-01-2288

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