

# 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

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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 ( $1.0 \cdot 10^6 \text{ s}^{-1}$ ) 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’<sup>1</sup> 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  $1.0 \cdot 10^6 \text{ s}^{-1}$  at 2)  $150^\circ\text{C}$  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  $1.7 \text{ mPa}\cdot\text{s}$  at  $150^\circ\text{C}$  [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  $2.4 \text{ mPa}\cdot\text{s}$ ) 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  $1.0 \cdot 10^6 \text{ s}^{-1}$  shear rate and  $150^\circ\text{C}$  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  $100^\circ$  and  $80^\circ\text{C}$ , also at a shear rate of  $1.0 \cdot 10^6 \text{ s}^{-1}$ . In addition, this work provided the initial

<sup>1</sup> 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  $1.0 \cdot 10^6 \text{s}^{-1}$ .

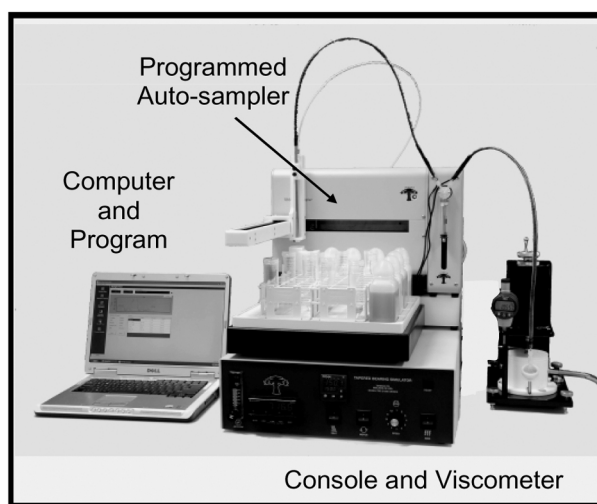


**Fig. 1. The Tapered Bearing Simulator Viscometer and supporting equipment for fully automatic operation.**

### 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.

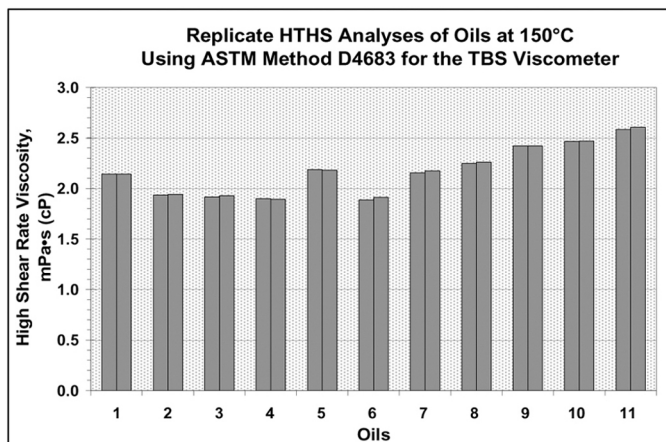


**Fig. 2. Precision of replicate determinations of high shear rate viscosities of eleven simulated low viscosity engine oils.**

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  $1.0 \cdot 10^6 \text{s}^{-1}$  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  $1.0 \cdot 10^6 \text{s}^{-1}$  shear rate was used with manual injection of the eleven oils.

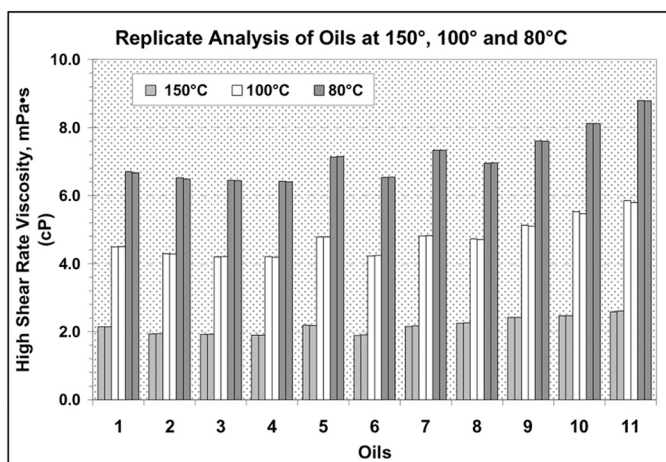


**Fig. 3. Precision of replicate determinations of high shear rate viscosities of eleven simulated low viscosity engine oils at 150°, 100° and 80°C.**