Very High Shear Rate, High Temperature Viscosity Using the Automated Tapered Bearing Simulator-Viscometer

By Theodore W. Selby, Savant, Inc.
Tom J. Tolton, Dow Corning Corp.

Presented at
Technische Akademie Esslingen
7th International Colloquium
Automotive Lubrication Conference
Esslingen, Germany
January 16-18, 1990

Very High Shear Rate, High Temperature Viscosity Using the Automated Tapered Bearing Simulater Viscometer

By Theodore W. Selby,
Thomas J. Tolton

Published in:
The Handbook of Tribology and Lubrication
Volume 6
1993

Very High Shear Rate, High Temperature Viscosity Using the Automated Tapered Bearing Simulator Viscometer

T.W. SELBY
Savant Inc., USA

T.J. TOLTON
Dow Corning Corp., USA
(formerly: Tannas Co., USA)

ABSTRACT

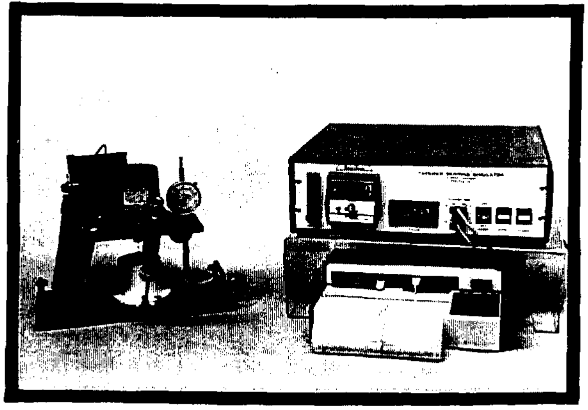
While the automation of the Tapered Bearing Simulator Viscometer has been dependent on several state-of-the-art developments, its ability to be used as an absolute viscometer with relatively high precision was a first requirement. In view of the ease of changing and measuring shear rates while in operation, the TBS was chosen to produce the data for engine bearing oil-film-thickness correlation through use with the empirical Cross Equation. Very good correlation is reported in the literature and these results confirm the use of the TBS in both automated and non-automated modes. A new test method shows considerable reduction in analysis time and an equally marked improvement in precision. The paper presents the background of the instrument; the steps of its automation; and its application to trenchant problems and new opportunities in the area of very high shear viscometry.

Introduction

The Tapered Bearing Simulator Viscometer (TBS), shown in Figure 1, has been used commercially since the early 1980s [Ref.1,2]. During the intervening years, several changes have been made reflecting developments in the art of temperature control, and its benefit in simplifying and automating the instrument. Much of this work has been done by the close cooperation of investigators in the Tannas Co. and in Savant, Inc. with whom both authors have been associated.

This paper presents further information on the development of automation for the TBS Viscometer as well as recent information on the original reason for its development -- correlation between the TBS and the engine bearing. However, for full understanding, the paper first presents some of the background factors leading to the development of TBS automation.

Figure 1



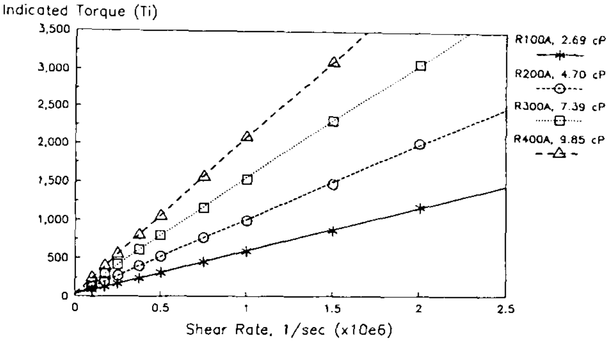
Background

A number of technical papers have documented the development of the TBS Viscometer [Ref.1 - 8]. Essentially, the instrument was designed with a geometry simulating that of the automotive journal bearing since this was one of the important potential applications for information from the instrument. The normally concentric cylinder arrangement for rotational viscometers was modified to have a slight taper along the lines of the Kingsbury Tapered Plug Viscometer [Ref.9] and, particularly, the work of Pike, et.al.[Ref.10].

In the development of the TBS Viscometer, a number of design requirements were set, the most important of which were to reduce extraneous friction to a minimum in order to increase the sensitivity of the viscous torque signal. The instrument has always performed well as a true viscometer by showing very linear torque/shear-rate calibration curves and coincident intercepts with Newtonian reference oils, as shown in Figure 2.

Figure 2

Newtonian Fluid Performance



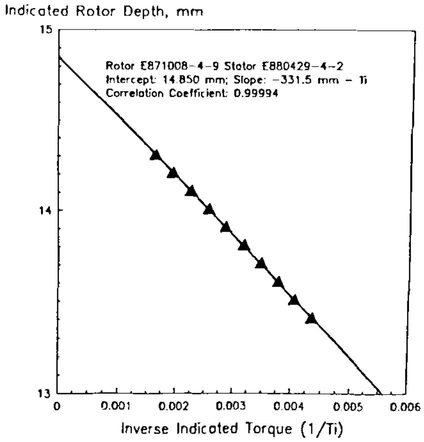
Importance of the Tapered Coaxial Configuration

The tapered design was primarily chosen for the development of the TBS Viscometer to permit vertical displacement of the rotor and stator and the ability to thereby vary rotor/stator clearances and, thus, shear rate. Adjustment of height was so easy because of the relatively light weight of the platform holding the motor, that it was quickly found possible to do this while the instrument was running. (As far as is known, at least among commercial viscometers, the TBS is unique in this regard.)

As a consequence, relatively early in the use of the instrument, independent studies by one of the authors and an associate showed [Ref.3] that the reciprocal of torque, **1/t**, varied linearly with the rotor height, **H**, as shown in Figure 3, as Newtonian theory would require. (Much earlier, unknown to the authors of Reference 3 at the time, Kingsbury [Ref.9] had demonstrated the same relationship with his Tapered Plug Viscometer which provided confirmation of the authors work.) This linear relationship of **1/t** vs. **H** was found to exist over a fairly broad range of rotor/stator displacement. Thus, this relationship indicated that not only was the TBS Viscometer effectively an absolute viscometer (an instrument with which viscosities can be calculated from the rotor/stator dimensions and rotor speed) but also that temperature effects were demonstrably negligible over a rotor/stator gap ranging up to about 8 microns.

Figure 3

Application of Absolute Method to Determine Rotor/Stator Gap Relationship



From these findings, it was possible to determine the operating shear rate quickly and experimentally on an absolute basis. That is, the theoretical contact height (TCH) of the rotor and stator could be determined where **1/t** became zero. From 1) the TCH, 2) the actual position of the rotor in the stator, and 3) knowledge of the rotor taper, the operating shear rate could be calculated. The unique capacity of the TBS to determine operating shear rates "on the run" was an important factor in simplifying the calibration of the instrument and automating it, as will be shown.

The presence of two flats on the rotor raised a question about the assumption of absolute viscometry from the mechanical data [Ref.11]. However, a theoretical analysis by DuParquet [Ref.12] indicated that the flats would have negligible effect at shear rates above 500,000 sec^{-1} where the error would be less than the repeatability of the instrument (see Table 1). As previously noted, the linearity of **1/T** vs. **H** in Figure 3 extends at least to a gap of 8 microns with a Correlation Coefficient of 0.9999+. In the TBS Viscometer, an operating gap of eight microns at 3600 RPM is equivalent to about 440,000 sec^{-1} which experimentally tends to confirm DuParquet's theoretical work.

Table 1

(Shear Rate) (Error)

$\dot{\gamma}$	$2\frac{T_f}{T_c}$
1 000 s^{-1}	23.9 %
2 000	21.6
5 000	17.0
10 000	12.8
20 000	8.9
50 000	4.9

(Shear Rate)

$\dot{\gamma}$	$2\frac{T_f}{T_c}$
100 000 s^{-1}	2.99 %
200 000	1.75
500 000	0.83
1 000 000	0.47
2 000 000	0.26

Thermoregulator and Heater Development Effects

It is perhaps stating the obvious to note that a high level of temperature control is a necessity for the practice of viscometry, particularly in high shear viscometry. The higher the shear rate, the more care which must be taken by design of the viscometer to control the effects of heat generated by viscous friction. In the case of the tapered geometry, higher shear rates are obtained by narrower gaps rather than by higher speeds. For example, the TBS Viscometer works at a gap of only 3.5 microns to generate a shear rate of 1,000,000 sec^{-1} at 3600 RPM. The thinness of the sheared film thus offers little opportunity for heat retention by the fluid and consequent distortion of the reasonably linear shear gradient across the gap is avoided. (Similarly, heat transfer to the oil film from the stator heater is essentially immediate.)

Much thought and effort has been expended to design the optimum thermoregulation for the TBS Viscometer. This effort has been encouraged by the rapid evolution of thermoregulators from simple on/off switches, to proportional bandwidths, to automatic reset, to derivative controls during the last few years and progress is continuing. This evolution has had a major impact on TBS development. Each new advance in thermoregulation has been incorporated as available and it must be emphasized that the present level of simplification and automation of the TBS is significantly dependent on the aforementioned advances in thermoregulator development, as will be evident.

The heating source has similarly gone through three stages of modification as technology progressed. At present, using modern high capacity heating membranes, heat is applied to the stator rapidly and uniformly. However, the thin membrane also permits excess heat to be quickly "dumped" through the membrane as well.

Continuous or Long-Duration Operation of the TBS

One of the field observations made earlier in the development of the TBS was that over a period of days or weeks, the indicated contact height determined by the **1/t** vs. H relationship increased slowly (the gap became smaller). While the slow change in indicated contact height did not affect the gathering of data (since the TBS is calibrated daily), the effect was puzzling.

At the outset, the effect was variously attributed to slow expansion of the wire-wound, flexible shaft coupling the rotor to the motor; deposits forming in the gap; changes in the housing holding the stator; or some combination. To eliminate the first-mentioned possibility and to decrease the rate of heat transfer up the relatively thick, wire-wound, flexible shaft, a thin, single-wire, flexible shaft was developed, which, at times, seemed to correct some of the phenomenon. However, it became obvious, that there was a more important factor to be considered.

Ultimately, it was found that deposits on the stator wall facing the rotor were the culprit. These deposits apparently formed slowly from decomposition of the base oil and/or additives at the high temperature of viscometric analysis. Certain strong solvents were found to be capable of removing the deposits, after which the TCH would drop back to original value.

As a consequence of this experience and in anticipation of the long-duration operation of the TBS Viscometer when automated, special fluids were chosen for reference oils and a so-called "idling fluid" was developed by the Mobil Oil Company for specific use in the TBS. This idling oil is recommended for use at any time when the instrument is waiting for further work. Tests have shown that the fluid will withstand weeks of exposure at 150°C and full rotor speed with insignificant wall effects or operating problems with the instrument when again used for viscosity determination. Most importantly, the TCH remained reasonably constant. Simultaneously with the development of the idling fluid, protective circuitry was developed for the TBS viscometer to shut down the unit in the case of overheating or power outages (the latter is important since the TBS Viscometer should not be started up with cold fluid in the gap set for operation at 1,000,000 sec^{-1}).

STANDARDIZATION OF THE TBS VISCOMETER

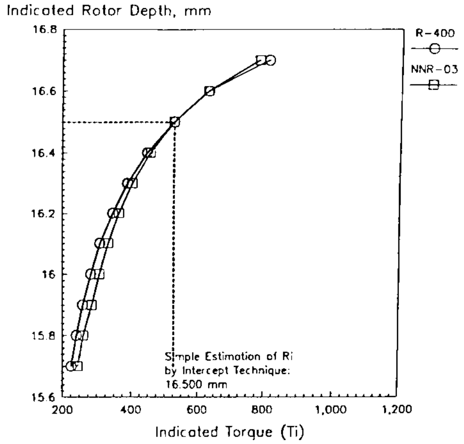
ASTM D4863-87 -- Relative Rotor Position Method

The initial laboratory utilization of the TBS Viscometer led to the formation of a Rotational Viscometer Task Force under the leadership of Robert B. Rhodes [Ref.8] within the appropriate group in the ASTM, namely Committee D2, Subcommittee 7, Section B. Reports on the activities of the Section and the Task Force have been recently published [Ref.2,8]. Essentially, this first method [Ref.6] employed a relative technique of comparing the viscosities of a Newtonian and a non-Newtonian fluid which at 1,000,000 sec^{-1} had identical viscosities. (However, the absolute technique possible with the TBS was used to establish the viscosity of the non-Newtonian oil at 10^6 sec^{-1}.) The round-robin study gave a repeatability of 3.1% and a reproducibility of 3.9% at the 95% confidence level.

The method, unfortunately, required plotting torque,**t**, versus rotor height, **H**, curves for the Newtonian and non-Newtonian fluids and interpreting their point of interception. Such interpretation could be difficult as shown in Figure 4. Coupled with the limitations of technology at the time (reflected by a manual-reset thermoregulator and a resistance-wired, silicon-rubber pad heater), the method was relatively slow and laborious. After the time required for calibration, relatively few samples (8 to 12) could be run in a day since sample-to-sample turn-around was a minimum of about 1/2 hour.

Figure 4

Ri Determination



Even this minimum turn-around time was possible, in fact, because the TBS Viscometer was designed so that no sample cleanup is necessary. That is, each sample "chases" the previous sample from the test cell while the rotor is spinning which helps to speed return to analysis. (However, the "chase" procedure was primarily chosen to avoid using solvents with their attendant problems of solvent contamination, odors, and the serious potential for either flash fires or toxic exposure conditions produced by some solvents at high temperatures).

Fifty-mL injections of each fluid were standard but 30-mL, injected 10-mL at a time -- with a few seconds pause between injections, was found sufficient to give complete interchange of oils in the shearing zone.

ASTM D4863-90 -- Absolute Rotor Position Method

It was experimentally found that the reciprocal torque technique also produced an essentially straight line with the non-Newtonian calibration oil. The significance of this finding was that the intercept of the Newtonian and non-Newtonian oil could be easily calculated as a unique point, rather than hand plotted and interpreted. This technical development, coupled with the previously discussed availability of

1. Advanced thermoregulators which, with automatic reset, could handle widely different viscosities,
2. High capacity heaters which don't block the heat flow from the stator,
3. Idling oil which could be left in the cell for weeks at a time without adverse effects, and
4. The ability of the TBS Viscometer to determine the TCH "on the run",

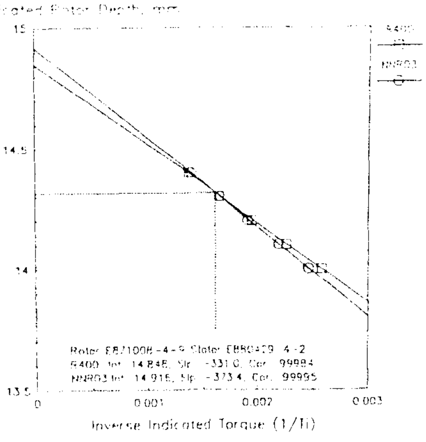
combined to make possible a faster, simpler method as well as to open the opportunity of automating the instrument.

The new version of the method requires bringing the instrument to operating temperature for about an hour to permit the thorough warming of the equipment. However, with the use of idling fluid and the safeguards built into the latest models of the instrument for unattended idling and automatic operation, a preferred alternative is to leave the instrument on all the time at operating temperature and with the rotor spinning at the desired gap so that the instrument is immediately ready for use at any time.

When the instrument is at temperature, the reciprocal torque vs. height technique is used to determine both the TCH of the Newtonian and non-Newtonian oils and their straight-line intercept as shown in Figure 5. The height of the rotor is adjusted to this intercept value and the instrument calibrated with four Newtonian reference oils. The method requires a modern thermoregulator. Using it, analysis time is now less than 10 minutes for sample turn-around. Significantly improved precision was shown when the ASTM round-robin conducted on the method in 1989 gave repeatability of 0.96% and a reproducibility of 2.59% at the 95% confidence level. The method and pertinent information on the round-robin is presented in ASTM Research Report D02-1253 [Ref.13].

Figure 5

Reciprocal Torque Intercept Technique
For Setting Gap



AUTOMATION OF THE TBS VISCOMETER

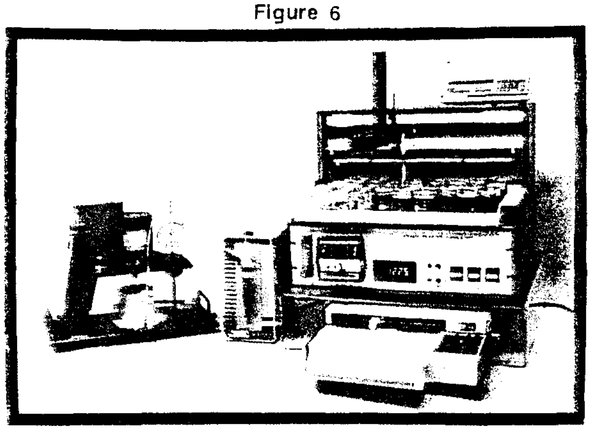
First Stage - Automatic Sampling

With studies showing success in

1. thermoregulation,
2. close heat control without operator attendance,
3. simple determination of the rotor position,
4. obtaining availability of a stable idling fluid, and
5. the incorporation of safe, continuous operation,

automation of the TBS Viscometer was now quite feasible. The first step was to set up a programmable sampler, as shown in Figure 6. This work has been covered in a past paper [Ref.5]. Essentially, the TBS Viscometer was calibrated as usual after which the sampler was activated to progressively analyze the unknown samples and reference fluids comprising the loaded sampler. In all, the sampler holds 70 tubes of oil. Use of a strip-chart recorder helped in the assimilation of data.

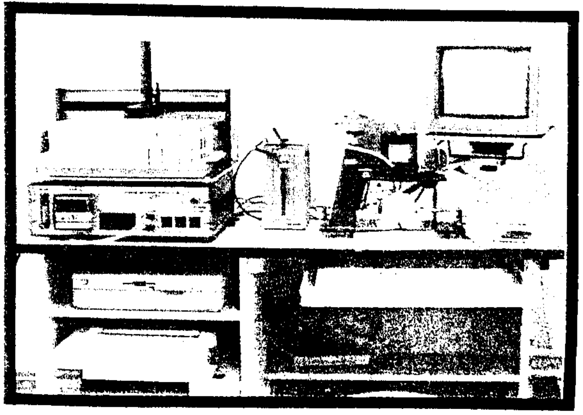
Figure 6



Second Stage - Semi-Automatic Calibration

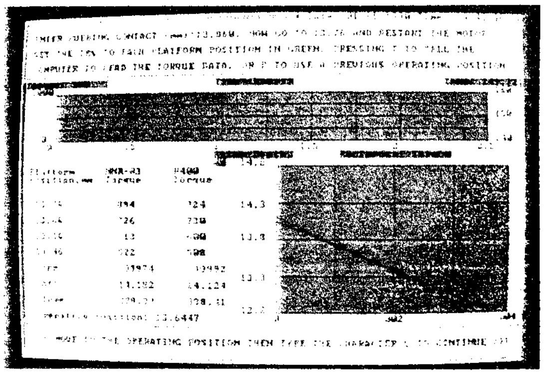
One of the more technically difficult parts of the use of any viscometer is calibration and, since the TBS Viscometer is usually calibrated (despite its absolute nature), the instrument is no different. While the new (absolute) technique considerably simplified the calibration, there was still a need for even simpler approaches. Fortunately, the microcomputer is just right for such applications and one of the systems operating in Japan is pictured in Figure 7.

Figure 7



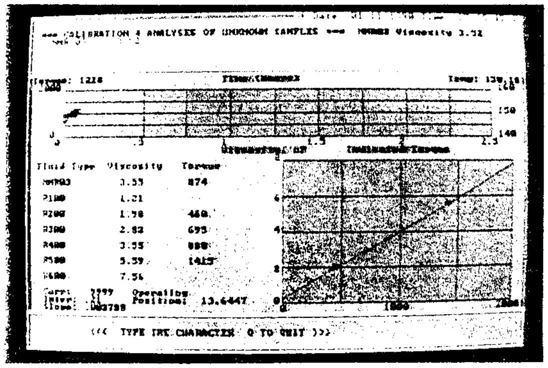
The second stage of automating the TBS Viscometer was to semi-automate the calibration. Using the computer keyboard, the operator is asked to answer certain questions on the computer keyboard regarding sample identification and location of calibration fluids on the sampling rack. The computer program then directs the automatic sampler to pick up certain reference oils for intercept analysis. When this is accomplished, the program then directs the operator to set the rotor at certain positions to generate necessary data to calculate the intercept of the Newtonian and non-Newtonian reference oils which plot is shown on the cathode ray tube (CRT) as pictured in Figure 8.

Figure 8



After obtaining the intercept value, the computer selects calibration oils from the sampling rack and automatically runs, computes, displays, and prints out the calibration data. At the same time, the computer checks the value of the non-Newtonian reference fluid and, if out of a preselected range, requires the operator to adjust the gap slightly and then reruns the calibration. After calibration, the computer displays the calibration curve, and the related values for the intercept, slope, and correlation coefficient, as shown in Figure 9. It then moves on to make the run, adding to the display the viscosities determined as well as the progressive, real-time, torque/temperature information received from the TBS Viscometer.

Figure 9



APPLICATIONS OF THE TBS/AUTOMATED-TBS VISCOMETER

General

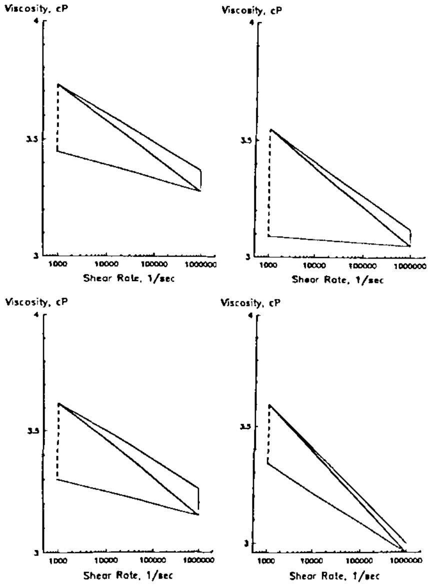
One of the obvious benefits of automation is that it permits the TBS Viscometer to be used with relatively untrained personnel who need to spend considerably less time in attendance. However, the un-automated TBS equipped with the proper thermoregulator can be used just as effectively as the automated version, albeit with considerably more attention. At the extraordinarily high shear rates possible with the instrument (above 2×10^{6} sec^{-1}), automation may improve precision but this has not yet been studied.

Singular Temperature - Multiple Shear Rate Data

One area of work using the TBS Viscometer for a portion of the necessary data, has been the study of the relationship between temporary and permanent viscosity loss (TVL and PVL). The work requires determination of the dynamic (absolute) viscosities of both the fresh and shear-degraded oils and the results, when plotted, form so-called Viscosity Loss Trapezoids (VLT) as shown in Figure 10 [from Ref.14]. These VLTs tend to be unique for each combination of VI improver type, concentration, and MW distribution, as well as varying to a lesser degree with the viscosity and solvency of the base stock. The patterns shown in Figure 10 are for four experimental SAE 10W-40 grade oils at 150^{o}C. It has been found that further data obtained on the same oils at 100^{o}C adds considerable information to the understanding of the behavior of and distinction between VI improvers as applied to lubricating oils and hydraulic fluids.

Figure 10

Engine Oil Viscosity Loss Trapezoids



The VLT approach was extended [Ref.7] using multiple shear rates on a different set of oils with the results shown in Figures 11, 12, and 13 for a single-grade SAE 40, a somewhat shear-labile SAE 10W-40, and a shear-stable SAE 10W-40, respectively -- the latter reflecting European blending and additive practices. (It should be remarked that this work was done at 100^{o}C using a Model 600 TBS Viscometer coupled with a Tannas liquid bath capable of handling the torque required and heat produced with the considerably higher viscosities encountered.)

As expected, the straight-grade SAE 40 shows a horizontally collapsed trapezoid (reflecting essentially no PVL or TVL). In unsurprising contrast to the latter oil, there are marked differences between the two SAE 10W-40s in regard to the **low-shear** PVL values. However, it is interesting that there seems to be relatively little difference between the two oils in regard to the **initial low shear** and **final high shear** viscosity values (taken at 2×10^{6} sec^{-1}). This suggests that low shear measures of permanent viscosity loss may be of little value in comparison to high shear viscosity data as related to bearing operating conditions. However, before this statement can be seriously considered, the effect of higher operating temperatures on viscosity must be determined. The next section treats this question.

Figure 11

Engine Oil Viscosity Loss
40

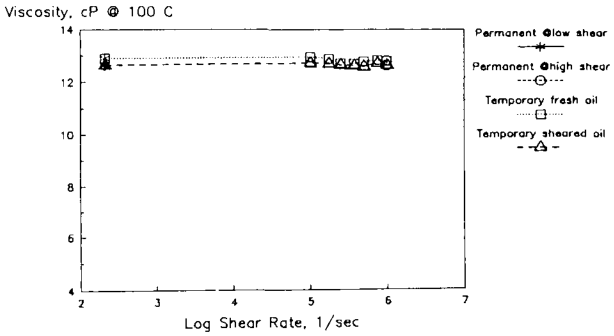


Figure 12

Engine Oil Viscosity Loss
10W-40

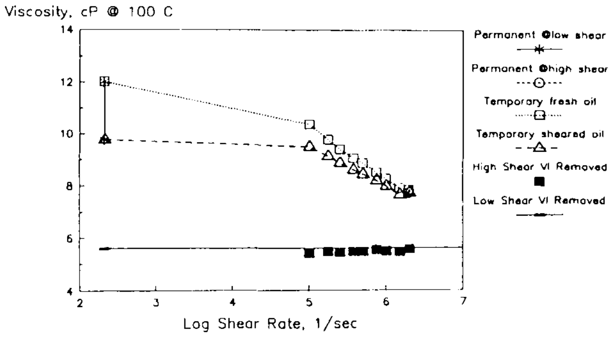
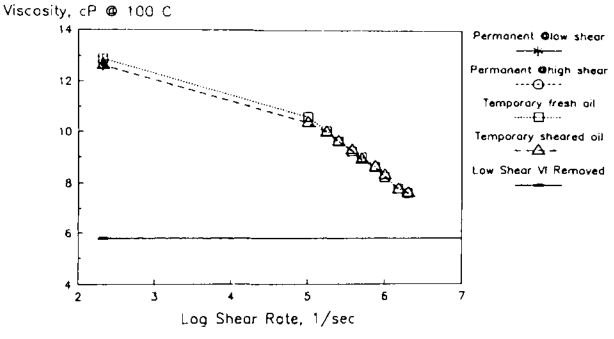


Figure 13

Engine Oil Viscosity Loss
10W-40



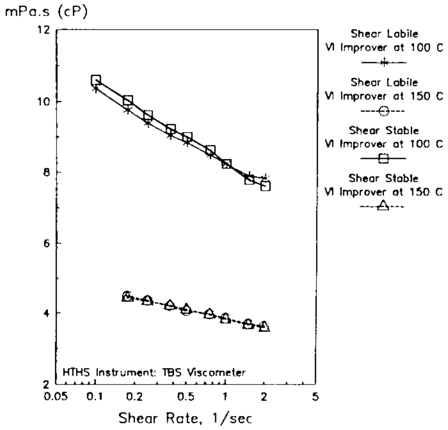
Multiple Temperature - Multiple Shear Rate Data

The advantages of being able to readily change shear rates (and determine them accurately) "on the run" as well as the capacity to easily change operating temperature, permitted some interesting data to be generated with the TBS Viscometer.

For example (and to answer the question raised in the last section), Figure 14 shows the shear labile and shear stable SAE 10W-40s of Figures 12 and 13 at 100 and 150 C. It is evident that the application of a higher temperature does not alter the similarity between the two in regard to their high shear viscometric properties, in spite of the obvious difference between the two in their low-shear PVL. Thus, it seems that low shear viscosity loss values are not relevant or predictive of high-shear response of bearings at operating temperatures.

Figure 14

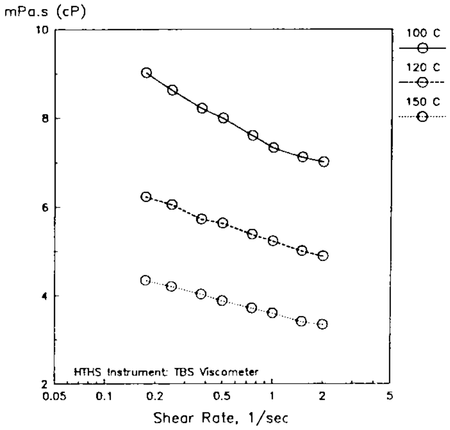
Engine Oil Temporary Viscosity Loss
Comparison of Shear Labile and Shear Stable SAE 10W40 Engine Oils at 100 and 150 C



Another study was to compare the TVL of an SAE 10W-40 engine oil at several temperatures. This information is shown in Figure 15. TVL (or "Shear-thinning", "pseudoplastic flow", or "orientation phenomena") is a well-know phenomenon occurring in VI improved lubricants (as well as in other solvated-polymer fluid systems). The phenomenon is explained by the macromolecule being stretched and oriented as flow occurs by the forces exerted on the macromolecule through its embedment in the matrix of the moving, solvating fluid -- in other words, the "viscous grip" of the base fluid (as well as other macromolecules in simultaneous flow). Condidering this "viscous grip" of the base oil on the expanded macromolecules comprising the VI improver, it would be expected that increasing shear stresses (increasing the orienting forces) would create more polymer orientation in flow (i.e. more TVL) at the same shear rate. This behavior is evident in Figure 15 by the difference in slopes of the curves. The study suggests that it would be of interest and perhaps of value to study macromolecular orientation at very high shear rates with different VI improvers and VI improved systems using widely different base oil viscosities and polymer solubilizing ability. For many years the theory and practice of polymer solution dynamics has wanted for very high shear viscometric data. That time would seem to have come.

Figure 15

Engine Oil Temporary Viscosity Loss
Comparison of Non-Newtonian Oil at Temperatures of 100, 120 and 150 C



Correlation with the 'Cross Equation'

Since engine bearings frequently operate at shear rates well in excess of 10^6 sec^{-1}, an empirical equation has been applied called the Cross Equation [Ref.15]:

$$\log \frac{\eta_0 - \eta}{\eta - \eta_u} = a + b \log\gamma + c/T$$

In which η is the high-shear viscosity at a temperature, T ($^\circ$K), and a shear rate, γ ; η_0 and η_u are the viscosities at zero shear rate and infinite shear rate, respectively. **a**, **b**, and **c** are empirical constants.

This equation, chosen on the basis of curve fitting, permits interpolation and extrapolation of viscometric data -- the latter being very significant because of the extraordinarily high shear rates produced by the operating engine. Figure 16 [from Ref.16] shows the agreement with the Cross Equation by several HTHS viscometers including the TBS. On the basis of the close agreement between the TBS Viscometer and the Cross Equation shown here and with other oils in a set of such oils, and because of the ease of spanning the desired shear rate range using the absolute technique available with the instrument, the TBS Viscometer was chosen to represent the group of HSHT viscometers. Subsequent solution of the Cross Equation by statistical regression of the viscosity/shear-rate data from the TBS, provided the viscosity data at the shear rates and temperatures needed for engine-bearing/oil-film-thickness correlation.

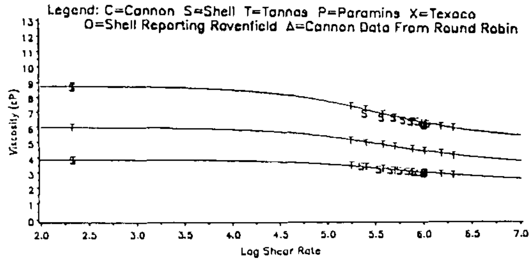


Figure 16

Plot of Observed and Predicted Viscosity vs. Shear Rate for Multigrade Oils
Comparison of Available Phase III Data With Predictions from Tannas Data
Only 100C, 120C and 150C Data Used
OIL=BFT−19

It should be mentioned that the close agreement of the TBS with the empirical Cross Equation tends to substantiate the information from both and, further, suggests that it may be of value to seek a theoretical basis for the equation.

Correlation with Engine Oil-Film Thickness Studies

The original motivation to develop the TBS Viscometer was to relate high-shear, high-temperature viscometric results to engine operation. During the time that the TBS Viscometer was being developed and improved by automation, highly significant work was being done by investigators into bearing oil film thickness. Their work and that of many others in the field was summarized relatively recently in a status report by the Engine Correlation Task Force of ASTM D2, Subcommittee 7, Section B [Ref.17]. It is recommended to the reader, that among other applications of the information contained, to use this report for a rich bibliography spanning a number of years.

Very recently an ASTM symposium on the subject brought to the fore the most recent developments and concerns of those cooperatively specifying engine oils [Ref.18]. The need for high-temperature, high-shear viscometry was frequently mentioned as one of the major issue to be faced -- one that could bring about changes in the way engine oils are presently specified.

With so much effort expended on developing the TBS Viscometer as a useful instrument, including work on the methods and the round-robins, by so many highly dedicated individuals, it is heartening to see that data from the instrument has been frequently used and proven helpful in generating dependable and consistent viscometric data in several of these engine correlation studies. Surprisingly high levels of correlation (R^2=0.98+) between the oil-film thickness and TBS-derived viscometric data were reported [Ref.19] which tend to confirm and underscore the long accepted assumption that high shear viscosity is the primary factor in developing bearing oil-film thickness.

From another point of view, the TBS Viscometer has met its original goal of simulating the bearing. At the same time, it has proven to be an instrument capable of broader viscometric applications to the determination of polymer solution dynamics.

Summary

The Tapered Bearing Simulator Viscometer has, for a number of years, been used in the field for producing high-shear viscosities but with a somewhat labor-intensive "relative" technique. The instrument has shown classic viscometric response and, because of the ability to set a variable rotor/stator gap while in operation, yields classical reciprocal torque versus gap relationship with Newtonian fluids. Thus, over a fairly broad range of rotor/stator gap, the instrument has been shown to be free of temperature effects and to operate as an absolute viscometer.

As a consequence of the discovery that a non-Newtonian reference oil will also give linear reciprocal torque versus rotor height curves, the method has been considerably simplified by more fully utilizing the TBS Viscometer's ability to be applied as an absolute instrument. As a consequence, calibration is faster and the precision of the instrument has been improved to 0.96% repeatability and 2.59% reproducibility at the 95% confidence level. Sample-to-sample turnaround time is now less than 10 minutes.

These developments have encouraged the incorporation of automation to further simplify its use by relatively untrained personnel and reduce the attention required to produce information.

Automation of the TBS Viscometer required the incorporation of advances in thermoregulation, heating membranes, safety controls for continuous running, and an idling oil permitting long, unattended runs with the instrument. Automation has been successfully accomplished and such units are now being used in the field.

Applications of the TBS to a range of studies and problems showed its use in generating multiple shear rate/multiple temperature data. One of the most important applications of this latter ability was in generating multi-shear, multi-temperature viscosities on oils used in engine-bearing oil-film-thickness correlation to determine the level of correlation. The results gave a Coefficient of Determination (R^2) of 0.98+ for a combination of single-grade and multigrade reference oils, confirming the value and pertinence of high-shear viscometry in general and the TBS Viscometer in particular. A high level of correlation between the TBS Viscometer data and the empirical Cross Equation suggested that the Cross Equation may have a theoretical basis.

Another area of study was opened in regard to the relation of Permanent Viscosity Loss (PVL) and Temporary Viscosity Loss (TVL). It was shown that two oils may have considerably different PVLs at low shear rates but this may not make any significant difference in their high-shear viscometric properties. This, in turn, suggested that, as far as bearing lubrication is concerned, perhaps PVL should be measured only at high shear rates. Further information related to this was in the production of Viscosity Loss Trapezoids which are an interesting and revealing way to examine the contributions and shear susceptibilities of VI improvers.

ACKNOWLEDGEMENTS

The authors wish to thank Prof. Dr.-Ing Bartz and his collegues for making such a colloquium possible.

Anyone involved in the development and standardization of an instrument and its attendent method knows the manifold effort required from many individuals. The authors do not have space to record individually these collegues from industry who worked together in yeoman manner to bring about lasting technical accomplishments. In particular the authors wish to note the strong and effective leadership given by Mr. Robert B. Rhodes who Chairmanned the ASTM Rotational Viscometer Task Force through the trenches and minefields of such a technical mission.

In the working environment of Tannas and Savant, there were again a number of individuals who helped either in the development of this paper or of past papers some of which data are presented herein. Our sincere thanks to them. In particular the authors would like to thank Dave Piasecki who has been deeply involved in TBS work virtually since the instrument was born. He has unselfishly given of his free time to smooth the way. Chiara Selby's supportive and skilled efforts in pulling the pieces of paper together to make this finished publication are gratefully acknowledged.

Taken together, the prayers and good wishes of friends and family were the deciding factor, and are most humbly appreciated.

Bibliography:

1. Piasecki, D.A.; Selby, T.W.; Smith M.F.: Development and Performance of The Tapered Bearing Simulator for High Shear, High Temperature Viscometry. 1981. PP. 11

   SAE Fuels and Lubricants Meeting. 81.10.19.-22. Tulsa, Oklahoma, USA

2. Smith, M.F.: History of ASTM Involvement in High-Temperature, High-Shear Oil Viscosity. High-Temperature, High-Shear Oil Viscosity - Measurement and Relationship to Engine Operation (ASTM STP 1068). 1. Edition. Philadelphia, USA: ASTM 1989, P. 3 - 13

3. Selby, T.W.; Piasecki, D.A.: The Tapered Bearing Simulator - An Absolute Viscometer. SAE Technical Paper Series, #830031. 1983. PP. 9

   SAE International Congress, Cobo Hall. 83.02.28.-03.04. Detroit, Michigan, USA

4. Hoshino, M: High Shear-Rate Viscosity and Its Measuring Technique. Lubrication (Japan). 30 (1985), 7-12

5. Tolton, T.J.: The Tapered Bearing Simulator -- Now an Automated Viscometer. SAE Technical Paper Series, #872045. 1987. PP. 5

   SAE Fuels and Lubricants Meeting. 87.11.02-05. Toronto, Canada

6. ASTM Standard Test Method for Measuring Viscosity at High Temperature and High Shear Rate by Tapered Bearing Simulator, D4683-87. In: 1989 Annual Book of ASTM Standards. Part 5.03. Philadelphia, Pennsylvania: 1989, P. 518 - 523

7. Tolton, T.J.: The Viscosity Losses of New and Sheared Multiweight Oil Formulations Determined at Multiple Shear Rates. SAE Technical Paper Series, #890727. 1989. PP. 10

   SAE International Congress. 89.02.27.-03.03. Detroit, Michigan, USA

8. Rhodes, R.B.: Development of ASTM Standard Test Methods for Measuring Engine Oil Viscosity Using Rotational Viscometers at High-Temperature and High-Shear Rates. High-Temperature, High-Shear Oil Viscosity - Measurement and Relationship to Engine Operation (ASTM STP 1068). 1. Edition. Philadelphia, USA: ASTM 1989, P. 14 - 22

9. Kingsbury, A.: Heat Effects in Lubricating Films. Mechanical Engineering. 55 (1933), 685 - 688

10. Pike, W.C.; Banks, F.R.; Kulik, S.: A Simple High Shear Rate Viscometer - Aspects of Correlation with Engine Performance. The Relationship between Engine Oil Viscosity and Engine Performance - Part VI (SAE SP-434). 1 Edition. Warren, PA.: P. 47 - 55

11. Taylor, J.C.: Letter to CEC CL-23 members. 1984

12. DuParquet, J.P.R.: A Few Steps in the Development of Rotary Viscometry. PP.17

    Ravenfield Conference on Viscosity. 85.09.24.-26. Bolton, England

13. ASTM Research Report D02-1253. Available from ASTM Headquarters, Philadelphia, Pennsylvania, USA

14. Selby, T.W.; Peoples, M.C.: Applications of Dynamic Viscosity at Low Shear and Higher Temperatures. STLE

    Society of Tribology and Lubrication Engineers 1988 Annual Meeting. 88.05.9.-12.

15. Cross, M.M.: Rheology of Non-Newtonian Fluids; A New Flow Equation for Pseudoplastic Systems. Journal of Colloid Science 20 (1965), P.417

16. Report to ASTM by Melanie Tobias of Texaco, Inc. Used with permission of Serge Cryvoff, Chairman of Bearing Oil Film Thickness Task Force, Section B, Subcommittee 7, ASTM D2. 89.12.04. PP. 41

17. Report from Engine Correlation Task Force; ASTM D2, Subcommittee 7, Section B: The Relationship Between High-Temperature Oil Rheology and Engine Operation - A Status Report. ASTM DS-62. ASTM, Philadelphia 1985

18. Spearot, J.A.; Editor: High-Temperature, High-Shear Oil Viscosity - Measurement and Relationship to Engine Operation, STP 1068.
    1. Edition ASTM, Philadelphia 1989

19. Spearot, J.A.; Murphy, C.K.; Deysarkar, A.K.: Interpreting Experimental Bearing Oil Film Thickness. SAE Technical Paper Series, #892151. 1989. PP. 14

    SAE Fuels and Lubricants Meeting. 89.09.25.-28. Baltimore, Maryland