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Viscometry of New and Used Engine Oils at Engine Shear Rates - Application of the Automatic TBS Viscometer

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ABSTRACT

Very high shear rate viscometry at levels commensurate with the operating shear rates in the modern passenger car engine, has been developed around a multispeed Automatic Tapered Bearing Simulator (ATBS) viscometer. The instrument and technique are shown to be repeatable with both Newtonian and non-Newtonian oils over the shear rate range of 0.53 million to 5.33 million sec^{-1}. Both the ATBS and its extended shear rate range have been applied to determine the viscosity of new and used oils at 150°C as well as the effects of such factors as fuel dilution and carbonaceous agglomerates.

INTRODUCTION

THE PAST: BACKGROUND OF MODERN HIGH SHEAR RATE VISCOMETRY - The authors thought that background on the 30-year development of today's high shear rate viscometry would be helpful in understanding its past importance and present challenge.

The Need - By the mid-70s, after decades of reliance on the comparatively low shear rate kinematic viscometer, the need to develop and incorporate high shear rate viscometry into engine oil specifications came about in this somewhat indirect manner:

On the basis of reported data [1, 2], a request was made by the Coordinating European Council (CEC) to the SAE in 1974 to form a new SAE 15W-40 engine oil classification positioned between the already extant SAE 10W-40 and 20W40 classifications.

The technical basis of the CEC request was to allow formulation of engine oils which would have higher levels of hydrodynamic lubrication at European engine operating temperatures, particularly in passenger car diesel engines. Low temperature properties were of less concern in central Europe [3].

SAE Study Group - In response to this indirect request for better high temperature hydrodynamic properties, the SAE appointed a study group to determine the merits of the request from both the classification issues and the more important need to develop the ability to measure viscosity under conditions representative of those required in engine hydrodynamic lubrication.

In 1975, the SAE study group recommended not only acceptance of the request from CEC but that the SAE should call for development of high shear rate viscometry at operating engine temperatures by which to classify engine oils for use.

ASTM HTR Task Force - The SAE 15W-40 classification was incorporated in the SAE Viscosity Classification System in late 1975 and in 1977 a request was made by SAE to the ASTM's Committee D2 to undertake the task of developing suitable high shear viscometry. In response, a High Temperature Rheology (HTR) Task Force under Marvin Smith was formed by Subcommittee 7 of Committee D2 [4].

A number of laboratories had one-of-a-kind concentric cylinder and capillary high shear viscometers [5-16] of varying calculated maximum shear rates ranging up to 1.2 million sec^{-1}. However, no broadly available, comparatively inexpensive, high shear viscometers were available. Smith, with his technical background and his role as chairman of the HTR Task Force, sought development of a commercial high shear rate rotational viscometer [4] as a method closely simulating the automotive journal bearing.

Operational characteristics of such a viscometer were defined as being capable of generating a million sec-1 at 150°C [4]. This was a set of viscometric conditions that had been selected by the SAE as relevant to hydrodynamic lubrication in engines [17] and later supported by consensus of viscometrists and engineers [18]. In fact, Smith had previously calculated that shear rates in an engine bearing might be between 5 million and ~20 million sec-1 [4] but considered that with the limited ranges of viscometers at that time it was not reasonable to ask for shear levels above 1 million sec^{-1}.

An Old/New Approach to Rotational Viscometry - Kingsbury had developed the tapered rotational viscometer (called the Tapered Plug Viscometer) in the very early 1900s [19, 20]. His and Needs' [21] findings were not applied until the late 1970s when Pike and his associates [9] turned the direction of rotational viscometry once more to a tapered geometry by incorporating opposing flats on the side of the rotor which had previously been shown effective by D. Kim and his co-workers in the development of the Cold Cranking Simulator [22].

Using Pike et al.'s approach, a similar flat-containing rotor geometry with a patented torque measurement technique led to the commercialization of the Tapered Bearing Simulator (TBS) viscometer in 1980 [23, 24]. With the designed capacity to change rotor height while operating, the TBS was later shown capable of operating as an absolute viscometer [25].

Two years later, in 1982, another rotating viscometer was developed and marketed with geometry also similar to that of Pike et al., [9]. It was called the Ravenfield Tapered Plug Viscometer (TPV) [26] recalling the name of the Kingsbury device previously mentioned [21].

High Shear Capillary Viscometry – Although reservations had been expressed earlier by Appeldoorn and Devore [27], in 1986 a commercial high shear rate capillary viscometer [28] was designed which successfully controlled capillary temperature. Discrepancies between high shear rate rotational and the new capillary viscometer led Girshick to show [29] that, with non-Newtonian fluids, possible viscous heating effects in the high shear rate capillary could not be distinguished from shear thinning effects. A subsequent ASTM report [30] concluded that the operating shear rate at the capillary wall should be increased by 40% to agree with the TBS and TPV rotational viscometers which themselves gave similar viscosity values.

Actual Shear Rates in Automotive Engines – As Smith's calculations had anticipated [4], Bates and Benwell's innovative studies of the running engine's bearing oil film clearance showed that actual shear rates experienced by reciprocating engines and journal bearings could range up to above 20 million sec^{-1}. However, depending on the bearing temperature and oil viscosity, most operating conditions were between 4 million and 10 million sec^{-1} [31]. From these views it was evident that further advances in viscometry were needed to obtain shear rates reflecting the lubrication needs and friction losses experienced by modern engines.

THE PRESENT: THE CHALLENGE TO REACH ENGINE SHEAR RATES - Over twenty years have passed since the first generally available high shear viscometer was developed and applied to the specification of engine oil viscosity. The limitations of only being able to obtain 1 million sec^{-1} when engines operated at considerably higher shear rates has been a challenge for all who have been involved in viscometrically simulating hydrodynamic lubrication.

Past Efforts With Fresh Engine Oils - To approach this need for information and understanding, the TBS viscometer was extended to shear rates up to 2 million sec^{-1} [32] by reducing the rotor-stator annulus. This was not considered enough and more recently the instrument was modified to cover a shear rate range of over 6 million sec^{-1} [33, 34, 35] by incorporating higher rotor speeds.

Final Step: Analysis of Used Oils - A limitation for some high shear rate viscometers has been the analysis of used engine oil. With its rotor design, analysis of used oils has not been a problem for the TBS at its normal operating annulus of 3.5 μm for 1 million sec^{-1}. However, annuli less than 2.0 μm needed for higher shear rates also limited the TBS to fresh oils.

Automation - The TBS with its "chase-replace" sampling technique has made the instrument adaptable for automation and this was partially accomplished [32] in 1990. However, for routine analysis, full automation has been a goal sought by the authors.

This paper presents the application of a fully automated TBS to the investigation of both fresh and used oil viscosity at shear rates from 0.5 million to over 5 million sec^{-1}.

INSTRUMENT AND TECHNIQUE

INSTRUMENT - A fully automatic Tapered Bearing Simulator (ATBS), shown in Figure 1, was used to set the initial shear rate of the oils studied after which manual speed selection was applied to obtain the range of shear rates desired. Operation at any chosen shear rate requires calibration, sample injection, and control of rotor position by a computer program. The entire setup is shown in Figure 2.

Precision of the instrument requires essentially identical tapers of the rotor and stator which then form a matched cell. At some chosen closely controlled speed, the torsion of the motor turning the rotor within the oil-filled stator produces a torque on the load cell (which was especially designed for high sensitivity). The arrangement is sketched in Figure 3. This torque response of the load cell is proportional to the value on

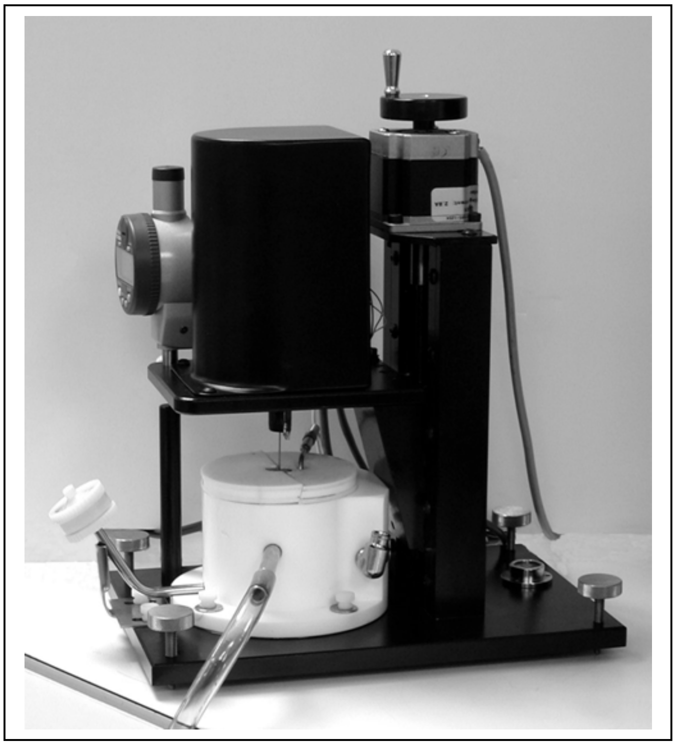

Figure 1 – Automatic Tapered Bearing Simulator (ATBS) Viscometer showing precise stepping motor drive on elevator fixture at right and digital sending micrometer on left.

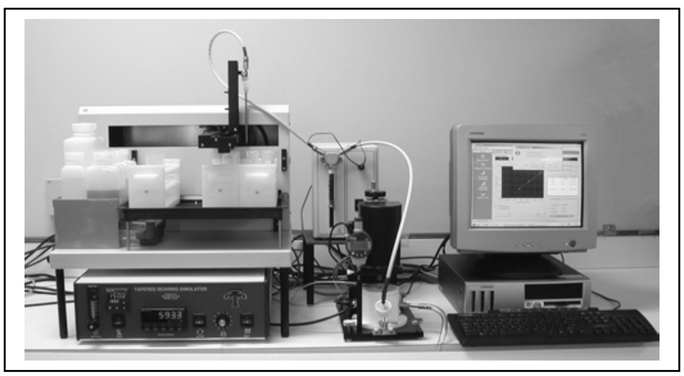

Figure 2 – ATBS Viscometer setup showing, left to right, autosampler over TBS multi-speed console, ATBS in front of autosampler pump, computer monitor, and work station.

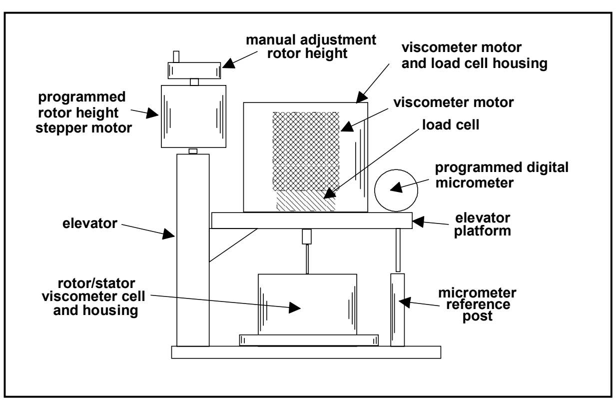

Figure 3 – Schematic sketch of ATBS Viscometer setup showing arrangement of stepper motor, elevator, rotor drive motor, in-line load cell, viscometer cell, and programmed digital micrometer.

the console display as well as used for calculation of available viscosity by the computer program.

ROTOR SPEEDS - Rotor speed is chosen from 12 available dial settings which establish precise speeds between 800 and 8000 rpm (within 1% of speed chosen). The speeds and equivalent shear rates are shown in Table 1.

Table 1 - Rotor Speeds and Shear Rate

Dial Set	RPM	Shear Rate, Million Reciprocal Seconds		
1	800	0.100	0.53	1.00
2	1,500	0.188	1.00	1.88
3	2,000	0.250	1.33	2.50
4	2,500	0.313	1.67	3.13
5	3,000	0.375	2.00	3.75
6	3,500	0.438	2.33	4.38
7	4,000	0.500	2.67	5.00
8	4,500	0.563	3.00	5.63
9	5,000	0.625	3.33	6.25
10	6,000	0.750	4.00	7.50
11	7,000	0.875	4.67	8.75
12	8,000	1.000	5.33	10.00

ATBS Calibration -To prepare for the multi-shear rate studies, the TBS 2100E is calibrated for 1 million sec^{-1} by the computer program at a speed of 1500 RPM at 150°C. This yields the range of shear rates shown in the shaded column of Table 1.

Rotor depth setting - As a consequence of the tapered relationship between the rotor and stator, the computer first establishes the rotor position to produce a gap yielding 1 million using the principle of reciprocal torque [32, 34] on both the Newtonian and non-Newtonian reference oils. (The two oils are blended to have the same viscosity at the desired operating temperature at 1 million sec^{-1}.) For example, the results shown in Figure 4 yield a rotor position of 15.67mm on the depth gauge.

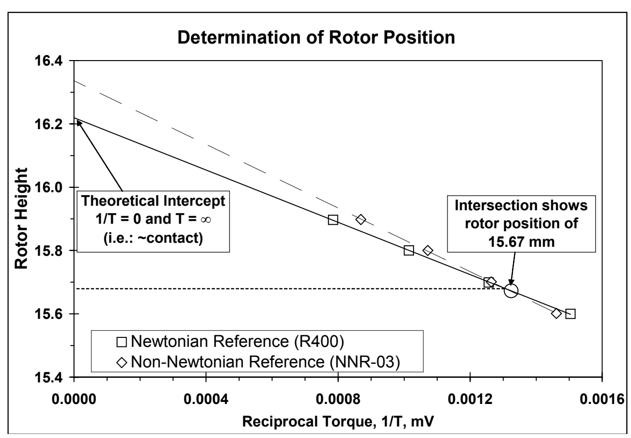

Figure 4 – Programmed technique for determining the position of the rotor. Rotor is automatically set to position determined in the stator.

Four-point Calibration - A four-point viscosity calibration conducted by the program is next performed using Newtonian reference oils having a sufficiently broad range of known viscosities. The computer program injects these oils into the rotor-stator cell and determines their torques. This information is then used by the program to evaluate the viscosity of the non-Newtonian reference NNR-03 (a reference oil with a viscosity of ~3.6 cP at 1 million sec^{-1}). With this information the program then checks if the determined viscosity of NNR-03 agrees with the value the user has previously entered into the ATBS program. If it is, as shown in Figure 5, then samples will be automatically started. If not, the computer will reinitiate rotor setting and recalibration.

TECHNIQUE FOR MULTI-SHEAR STUDY - Using air cooling of the rotor-stator cell, the 1,500 RPM speed

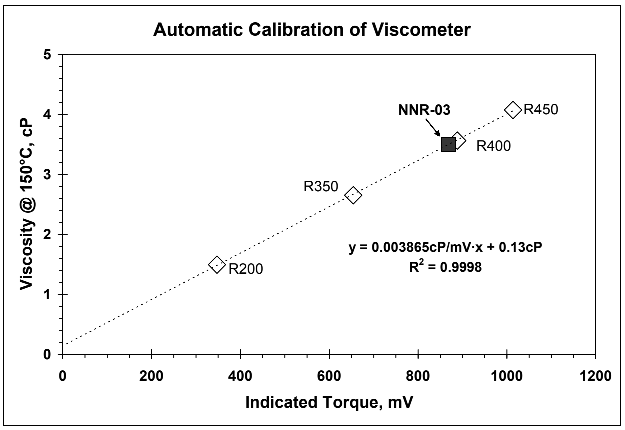

Figure 5 – Programmed technique for calibrating the ATBS and re-checking correct rotor position using known non-Newtonian Reference NNR-03.

selected for this study permitted a shear rate range from approximately 0.53 million to 5.3 million sec^{-1} using rotor speeds from 800 to 8000 rpm (see Table 1).

To have confidence in such broad shear rate range studies, it is first necessary to determine the degree of linearity of the relationship between load cell torque and motor speed using a Newtonian oil having a viscosity reasonably representative of engine oils at 150°C. Specifically, in such analysis, a Newtonian fluid should produce a highly linear relationship between the speed of the rotor and the torque generated. Any significant deviation from that linear relationship usually indicates that the heat effects from viscous shearing are operating (although other effects may also be involved). Rouse showed that this heating effect increases linearly with viscosity and exponentially with the square of the shear rate [36].

If good linearity can be obtained ($R^2 > 0.999$), calibration of the TBS by changing speeds is a convenient technique and requires only one Newtonian oil whose torque is measured at several shear rates. In these studies, a Newtonian fluid identified as R350 by the authors' company was used. However, any known Newtonian fluid may be used. At the temperature of 150°C, torque values were taken at each of 12 speeds from 800 to 8000 rpm. For reasons mentioned earlier, R350 was selected because of its close proximity in viscosity to those of the engine oils also being tested.

The linearity of the data obtained with reference oil R350 is shown in Figure 6. It is evident that over this shear rate range, viscous heating is controlled and the viscometer is giving linear response with a Coefficient of Determination, R^2, of 0.9998. The non-zero intercept indicates a pre-loading of the load cell and does not affect the precision of any viscosity determination since the automatic calculation of viscosity subtracts the intercept value.

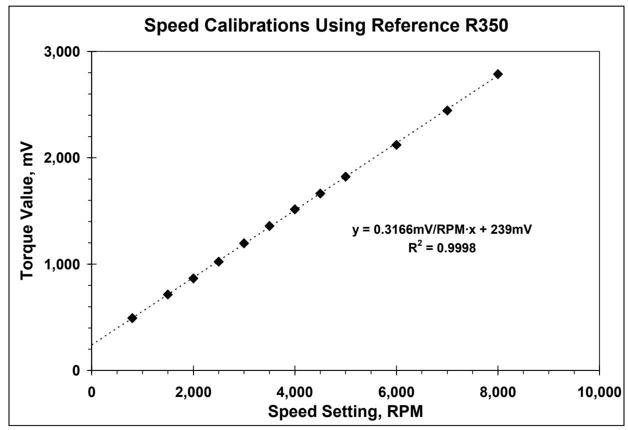

Figure 6 – Calibration of the ATBS using torque-rotor speed technique.

RESULTS

REPEATABILITY OF DETERMINING NEWTONIAN BEHAVIOR – Four replicate analyses of R350 are shown in Figure 7 which were generated over the period that the study was conducted and not at one time. Repeatability of speed calibration of the TBS 2100E and of the technique is evident. In this work, the ATBS

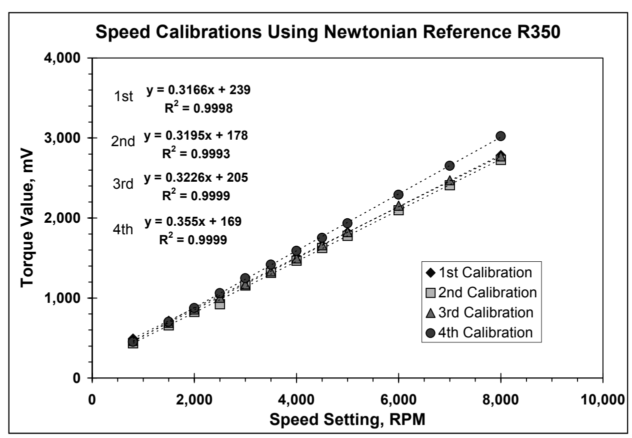

Figure 7 – Repeatability of the torque-rotor speed technique.

automation program was used to set the initial rotor position for 1 million sec^{-1} at 1,500 RPM rotor speed using the protocol illustrated in Figures 4 and 5.

Following this, the multiple speeds were manually chosen starting at 800 RPM and ending at 8,000 RPM.

REPEATABILITY OF DETERMINING NON-NEWTONIAN BEHAVIOR – Repeatability of determining Newtonian oil viscosity (as indicated in Figure 7) leads to the more demanding question of the repeatability of measuring the viscosity of non-Newtonian oils, the most common form of engine oils. Figure 8 shows the results of five runs on the non-Newtonian reference fluid NNR-03. These analyses followed each of the four calibration runs of Figure 7 and, in one case, the analysis was also the last run of the set. The runs replicated well as shown with somewhat more data scatter at lowest speeds where sensitivity

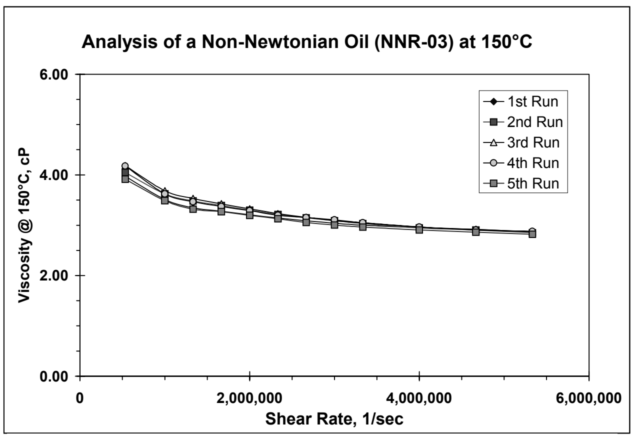

Figure 8 – Repeatability of the analysis of a non-Newtonian fluid using the multispeed-calibrated ATBS.

would be expected to be somewhat lower.

Average temporary viscosity loss (percent difference between the initial and final viscosities) over the shear rate range was calculated to be 29.9%.

<u>Comparison of Shear Rate Range Overlay</u> - NNR-03 was also analyzed over two shear rate ranges by re-

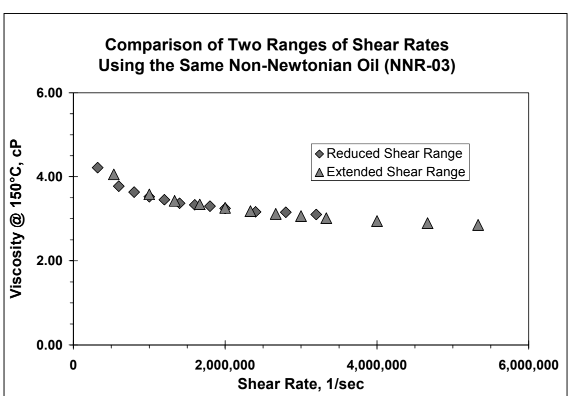

Figure 9 – Two shear rate ranges of same non-Newtonian oil.

setting the rotor-stator gap. Results are shown in Figure 9. One range is from 0.32 million to 3.2 million sec^{-1}, while the other is from 0.53 million to 5.33 million sec^{-1}. Viscosity values over the latter shear rate range are the average of the five runs previously shown in Figure 8. The values from the two shear rate ranges form superjacent curves and thus show the ability of the TBS to extract similar data from different rotor setting depths. In both cases, the rotor depth was first set by the ATBS program before the manual speed scan.

Viscosity of the NNR-03 was found to vary from 4.22 cP at 0.32 million sec^{-1} to 2.85 cP at 5.33 million sec^{-1} -- a viscosity decrease of 32% (somewhat greater than the 30% obtained from the data of Figure 8) as a consequence of the value taken at lower shear rate.

ANALYSES OF FRESH ENGINE OILS - For the purposes of this paper several fresh oils of both similar and different SAE Classification were analyzed over the shear rate range of 0.5 to 5 million sec^{-1} at temperatures of 150°C. Newtonian Reference Oil R350 was run first to establish the baseline calibration data for each set of analyses. Fresh and used oils were run in the same format.

These data are shown in Figure 10. Each oil shows some degree of decreasing viscosity from 0.5 million to 1.5 million sec^{-1} after which they decrease more gradually to a plateau at around 3.25 million sec^{-1}, sometimes called the “second Newtonian region”.

Oil E, the SAE 10W40 shows both the largest decrease in viscosity at 0.5 to 1.5 million sec^{-1} as well as the

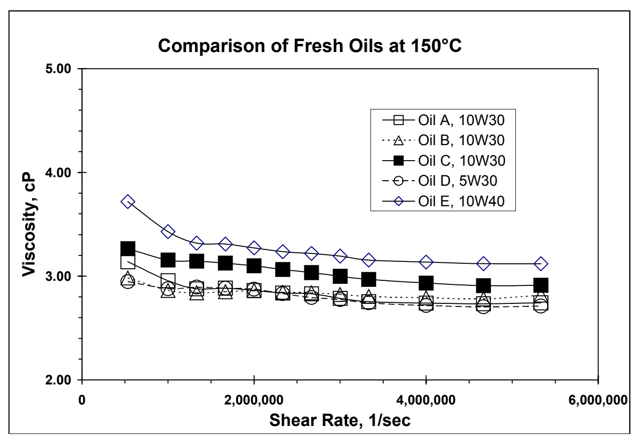

Figure 10 – Analysis of five fresh non-Newtonian engine oils of various SAE classifications.

highest overall viscosity at all shear rates with 3.81 cP at the 5.3 million sec^{-1}. Of the three SAE 10W30s, Oil C is consistently higher in viscosity over the shear rate range explored and, at 5.3 million sec^{-1}, has a viscosity of 2.91 cP. At the highest shear rate, the SAE 5W30 (Oil D) has the lowest viscosity of the group at 2.72 cP.

ANALYSES OF OIL B - Although a number of oils have been studied, for the purpose of this initial paper, one popular brand, Oil B, has been analyzed in greater detail by looking at its viscometric characteristics in fresh and used condition from several engines of widely varying ages, different designs, and used in different driving patterns. Table 2 identifies some pertinent information on the vehicles using Oil B.

Fresh Oil B - Figure 11 shows the response of fresh Oil B to the range of shear rates. Essentially, the oil behaves

Table 2 - Analyses of Used Oil B (SAE 10W30, API/ILSAC SL/GF-III)

Oil Information		Vehicle Information			
Sample	Oil Miles	Type of Driving	Model Year	Engine Type	Engine miles
Oil B	0	Fresh	--	--	0
Oil B1	3100	?	1997	5.3L V-8	73,193
Oil B2	3200	?	2000	5.3L V-8	45,518
Oil B3	3500	Local delivery	1994	3.1L V-6	87,144
Oil B4	3592	Country/City	2001	2.7L V-6	16,716

in a Newtonian manner over the shear rate range shown. The viscosity at highest shear rate of over 5 million sec^{-1}

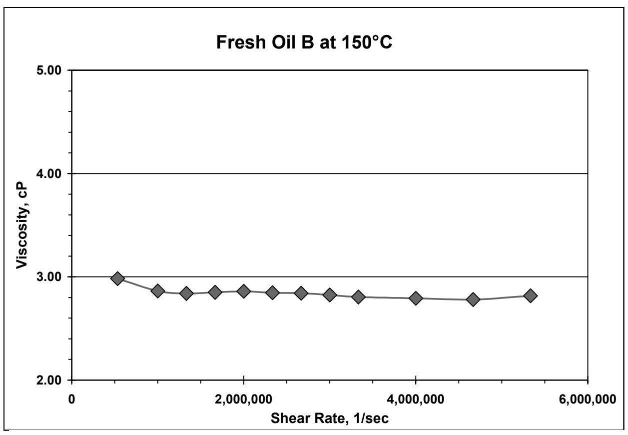

Figure 11 – Analysis of fresh Oil B over a wide shear rate range.

was 2.82 cP.

Used Oil B – The sources of the used oils and related information are given in Table 2. Drain intervals were indicated to be relatively the same – from 3100 to 3600 miles.

Three engine types are indicated with the oldest, a 3.1 L, V-6, made in 1994 and the vehicle carrying just over 87,000 miles. In contrast, the youngest is a 2.7L V-6 with 16,700 miles on it made in 2001. Two of the engines were 5.3 L, V-8s. While only two driving patterns were known (for the 3.1 and 2.7 L engines), these patterns were considerably different.

Oil B1 - Figure 12 shows the results of the ATBS viscometer analyses of the five samples of Oil B. Used Oil B1 is viscometrically very similar to the fresh Oil B despite the fact that this vehicle has over 73,000 miles on it. Presuming the original engine is in the vehicle and not knowing the driving pattern, this suggests that the engines of older vehicles can be relatively mild in engine oil degradation.

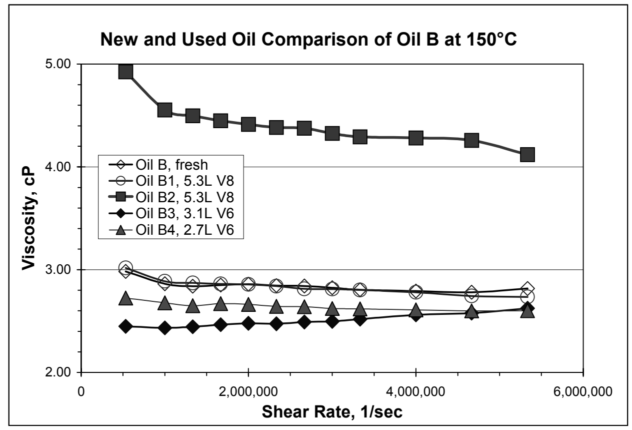

Figure 12 – Analysis of samples of used Oil B from several engines over a wide shear rate range.

Oil B2 - In contrast, Oil B2 was a highly particle-contaminated oil even though its change interval was indicated to be about the same as Oil B1. The comparatively high concentration of carbonaceous material in Oil B2 was almost certainly the cause of the extraordinarily high level of viscosity shown in Figure 12 for this oil.

It will be noted that the viscosity of Oil B2 drops markedly with shear rate. One reasonable conjecture is that at this level of particulate contamination, the particles may have begun to form carbonaceous agglomerates – a loose grouping of carbonaceous particles containing considerable constrained oil.

If the viscosity contribution of oil-containing agglomerates suspended in oil is higher than the free particles suspended in oil, then under the increasingly high shear rates experienced, it would be likely that such agglomerates would be broken up and the viscous contribution of the oil-entrapping agglomerates would be reduced. The viscosity of Oil B2 changes from 4.92 to 4.12 cP under increased shear rate (and shear stress) – a decrease of 16%.

It is planned to reanalyze this oil under both increasing and decreasing speeds. If the viscosity falls and doesn't recover quickly (time is required for agglomerate reformation) – that is, if the viscosity shows hysteresis – it would indicate that the above conjecture is valid.

Oil B3 - Oil B3 was different from the others in that its viscosity increased with increasing shear rate. Table 2 shows that Oil B3 was from a local delivery truck of high mileage. Usually, such trucks are exposed to much stop-and-go driving which causes fuel dilution. Not unexpectedly, Oil B3 was considerably lower in viscosity than the other used Oil B samples and had an evident fuel odor. The progressive increase in viscosity with exposure to the TBS operating temperature of 150°C was viewed as caused by evaporation of the fuel and not a function of shear rate increase. Such response of fuel-contaminated engine oil yielding increasing viscosity of the oil with time of analysis has been experienced in the laboratory at 150°C even without change of shear rate.

Oil B4 - Oil B4, from a vehicle having both city and country driving patterns, shows a response to shear rate very similar to that of the fresh Oil B except that the viscosity-shear curve is displaced evenly to a lower viscosity level. This may indicate that the oil has been diluted by some oil-based aftermarket additive. Further work is planned by the authors to determine whether this is the case**.**

DISCUSSION AND CONCLUSIONS

Data shown in this paper indicate that the automatic Tapered Bearing Simulator (ATBS) viscometer is capable of reaching shear rates experienced by the bearings of the automotive engine. Moreover, its repeatability with both Newtonian and non-Newtonian oils over a broad shear rate range is good as shown in Figures 7 and 8.

Analysis of used non-Newtonian oils using the same techniques and shear rates as with fresh oils indicates that the response of these oils to the ATBS can give interesting and meaningful information about the condition of the oil and the manner in which the oil has been influenced by the engine.

The ATBS seems to be an instrument equally applicable to routine laboratory analysis as well as research. Recognizing the value of information comparing fresh oils and their used oil counterparts at engine shear rates, the authors are presently continuing to evaluate new and used engine oils from the field. In addition, they are setting up a program to evaluate engine oils before and after exposure to laboratory shear degradation and oxidation of oil in comparison to the degradation that these same engine oils experience in the field under the rigors of daily driving.

One viscometric aspect of the wide shear rate range of the data from the five fresh engine oils seems to be that, at the higher shear rates, all seemed to be close to, if not at, the second Newtonian region. This is the hypothesized region in which the oil behaves as though its viscosity has no further shear rate or stress dependence. If this is so, the viscometric information so obtained may make calculations of the fuel efficiency (as affected by viscous energy loss in the engine) much simpler.

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