

Impact of Viscosity Modifiers on Gear Oil Efficiency and Durability

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ABSTRACT

This paper is part one of a longer term comparison of viscosity modifier behavior in modern automotive gear oil (AGO) fluids and the impact of these properties on fluid efficiency and durability. This first installment will compare the rheological properties, including EHD film thickness and traction coefficients, of the fluids across broad operating temperature, shear and load regimes and correlate these findings with rig efficiency testing.

The effects of traction, EHD film thickness and high shear rheology on operating temperature are well documented and it is of particular interest to determine the extent to which different viscosity modifiers can beneficially impact these properties compared to a Brightstock-based SAE 80W90 grade fluid. The efficiency improvements of a VM would be for naught if it were not sufficiently shear stable and so comparisons are made between shear stable VM technologies.

The final discussion introduces new tapered roller bearing shear test conditions that correlate more closely to fluid shear in the field than the current 20 h tapered roller bearing shear test, CEC L-45-A-99.

INTRODUCTION

Modern, high performance automotive gear oil (AGO) fluids contain a polymeric additive commonly known as a viscosity modifier (VM). The VM profoundly impacts the rate of change of kinematic viscosity between 40°C (KV 40) and 100°C (KV 100) as defined by its viscosity index (VI). A high VI fluid is preferred because, in effect, it is better able to minimise the reduction in fluid viscosity by oil entrainment as the gear oil warms to operating temperature.

A VM that can impart a higher VI can, therefore, offer an increased temperature range over which the fluid will operate, reducing starting and extreme low temperature viscosities while maintaining desired

operating viscosity and further maintaining viscosity (hydrodynamic film protection) at elevated temperatures as described in Figure 1.

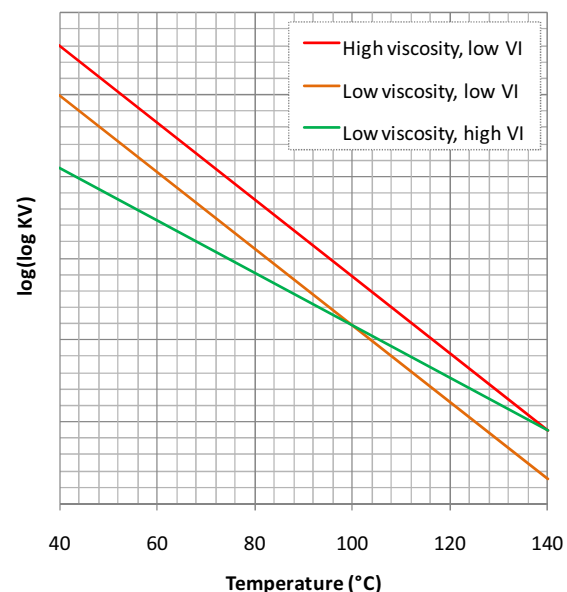


Figure 1: Viscosity-temperature profile of three fluids

The VM composition affects a number of readily measured properties key to efficiency including EHD film thickness and traction. However, the inclusion of a VM, a polymeric substance by nature, means the fluid may be prone to temporary and/or permanent shear loss depending on the nature of the polymer used.

Brightstock-based fluids cannot emulate the efficiency and cleanliness of high performance wide-span VM containing multigrade fluids, however, the oft proposed benefit of Brightstock (considered Newtonian or near Newtonian fluid) is that the fluid will not shear significantly in operation.

Herein we present comparative data showing that the efficiency gains of a VM can be substantial without

compromising fluid lifetime operating viscosity. The concluding section of the following discussion is based on the correlation of new shear screen test conditions with commercial vehicle field test shear data, which in combination with the fluid rheological and efficiency performance, demonstrates the new VM technology presented herein is well equipped to meet increasingly pressing efficiency and shear loss requirements.

AUTOMOTIVE GEAR OIL EFFICIENCY

For the consideration of efficiency during normal service an automotive gear oil (AGO) will operate predominantly in hydrodynamic or elastohydrodynamic regime as defined by the Stribeck plot (Figure 3).

As a consequence of the increasingly demanding shear requirements and relatively high viscosity for AGO, the VM can be present in high concentration and so can have a profound positive or negative impact on the fluid bulk properties. The correct selection of VM type is key to balancing the fluid properties with shear stability and should be carefully considered to ensure appropriate performance. There are many VM chemistry types available for consideration, and herein, we present a new VM alongside more traditional technologies.

The VM ideally would provide robust EHD and hydrodynamic film protection to the fluid while minimizing EHD traction and churning losses.

GEAR OIL FLUID EVALUATION

Previous studies have shown that a reduction in KV 100 can result in significant benefits under low load, high speed and vice versa under low speed, high load. However, if KV 100 remained constant the impact of the VM on efficiency can be isolated and correlated to the other rheological properties it affects. One might expect, based on the prior statement, that a flatter viscosity profile (high VI with minimal temporary viscosity loss overall) might provide the best balance of efficiency as a function of load and speed.

This study is primarily concerned with the impact of VM on fluid efficiency; the additive performance package was kept constant throughout. The primary impact of the additive package is in boundary contact and contribution to overall operating efficiency is minimal to losses incurred through churning. The fluids were prepared to meet the targets as follows:

- *Kinematic viscosity (100°C):* 17.5 cSt (mid SAE 90 grade viscosity)
- *Additive performance package (10 wt% treat):* A commercially available Total Driveline Fluid (appropriate for transmission and axle applications)
- *Base stock:* PAO-4 for VM fluids, Group II for Brightstock

A range of commonly available automotive gear oil VMs were selected and compared to a new dispersant viscosity modifier technology as described in Table 1.

	20 h KRL (SSI)	Description	Dispersant (yes/no)
New VM	3	ester olefin copolymer	yes
DPMA	8	poly(alkyl methacrylate)	yes
PAO100	1	poly(α -olefin)	no
PIB	6	poly(iso butylene)	no
Brightstock	1	complex hydrocarbon	no

Table 1: Viscosity modifier description

The kinematic viscosity at 100°C is the starting point for normalization of the blends and further blend data is included in Table 2 by VM type. The individual fluid data is representative of subsequent repeat blends performed. In each case kinematic viscosity at 100°C is not exactly 17.5 cSt, however, allowing for the adjustments in kinematic viscosity the fluids still maintain the same rank order as shown below.

	KV100 ^a (cSt)	KV40 ^a (cSt)	VI	BV40 ^b (cP)	POUR POINT ^c (°C)	HTHS ^d (cP)
New VM	17.58	102.5	189	41500	-57	6.02
DPMA	17.21	106.7	177	49000	-51	5.85
PAO100	16.92	112.8	164	57000	-48	5.36
PIB	17.63	127.2	153	88000	-54	5.56
Brightstock	17.52	174.7	103	TVTM	-27	5.05

a – Kinematic viscosity at 40°C (KV40) and 100°C (KV100), ASTM D2270-10

b – Brookfield viscosity at -40°C (BV40), ASTM D2983

c – Pour point (°C), ASTM D5950

d – High temperature, high shear at 150°C (HTHS), CEC L-36-90

Table 2: Comparative viscometric data for study

Based on the assumption that a contribution to fluid operating temperature range, efficiency and durability can be related to VI to a first approximation the data in Table 2 has been ranked by decreasing VI. The differences in the log(log KV) plot in Figure 2 appear subtle, however the Brightstock fluid is a substantial 50-86 VI points lower than any of the VM fluids. The positive impact of the high VI becomes particularly apparent at high temperatures for fluid film support and low temperature extremes for efficiency. In particular:

- Brightstock fluid is 160% higher in kinematic viscosity at 20°C than new VM fluid
- Brightstock fluid is 70% higher in kinematic viscosity at 40°C than new VM fluid

By design the comparisons are being made among VMs appropriate for AGO use as defined by low permanent shear loss by CEC-L-45 (20 h KRL, see final section), and so temporary shear loss might also be expected to be lower than for VM systems typical to other less stringent shear loss end uses.

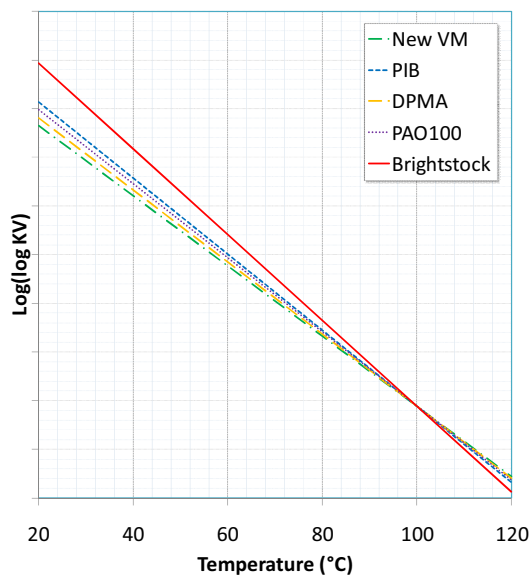


Figure 2: Log(logKV) plots showing effect of high VI fluids

Gear oils must exhibit good resistance to temporary and permanent shear loss with operating shear rates as high as $10^6 - 10^7 \text{ s}^{-1}$. High temperature, high shear viscosity (HTHS) is a well established measure of high shear rate film protection typically associated with engine lubricants. It is perfectly adequate to use HTHS to describe the temporary shear losses that may be observed in a gear lubricant also.

Upon examination of Table 2, it is clear there are a marked differences between those fluids containing VM and the Brightstock fluid, a key consideration as the drive to lower viscosity continues and film lubrication and protection may reach break point less quickly with an appropriate VM.

The trade off in VI-HTHS at equal viscosity is common place with traditional VM technologies.¹ Interestingly, in spite of having the most favorable VI the new VM is capable of sustaining the lowest temporary viscosity loss as defined by HTHS, again pointing toward a more sustainable efficiency-durability balance over broad operating conditions. In other words, the use of the new VM to improve the low shear rate kinematic viscosity-temperature profile has not been at the expense of temporary viscosity losses at high temperature and shear rates.

It is clear that all VM containing fluids improve VI, low temperature flow and HTHS viscosity to differing extents over Brightstock. The overall picture is more complex than this and we must also consider EHD film thickness, traction and operating efficiency over a range of temperatures, and of course, consider the relative shear stabilities.

Elastohydrodynamic (EHD) film thickness

The simple viscometrics heretofore are good initial indicators of the potential of a system to improve

efficiency and durability from low to high temperature extremes at low load, but the nature of the polymeric VM can have a profound effect on the elastohydrodynamic film thickness and traction also (Figure 3).

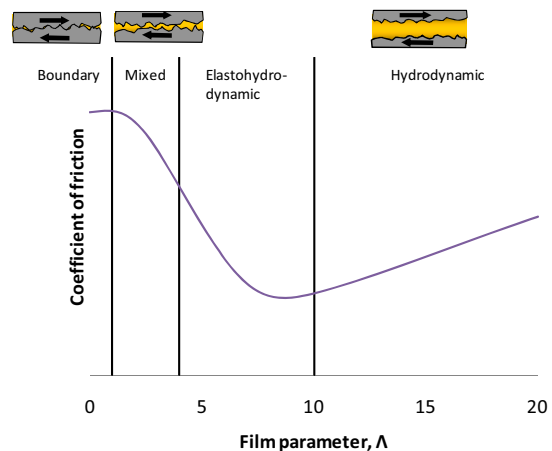


Figure 3: Typical Stribeck curve

EHD film thickness measurement was carried out using a commercially available ultra-thin EHD film thickness tester manufactured by PCS Instruments. EHD film thickness measurement Optical interferometry technique was used to measure fluid film thickness under rolling conditions in highly concentrated contact formed between a steel ball and glass disc. EHD films were measured from 40°C to 120°C at a Hertz pressure of 0.5 GPa.

Low speed and high temperatures are particularly discerning for a fluid's ability to provide film protection during stop-start driving such as prolonged urban drive cycles.

Figure 4 shows the EHD film thickness as determined by optical interferometry at 80°C with increasing speed for the different fluids. Overall the desire is to achieve a sufficient film at low speed to separate moving parts but with minimal frictional losses as determined by the EHD traction coefficients presented in the next section.

Previous work has described the influence of the functional groups in a range of DPMA's on EHD film thickness at low speed.² The paper described a range of DPMA's that, depending on their dispersant head group, had similar or lower film thickness to PIB at low speed. Under our test conditions all fluid systems provide similar film thickness at low speeds with the exception of the DPMA. Low speed film formation is particularly discerning for EHD protection.

As the speed increases and the moving parts begin to separate the relative magnitude in film thickness is lower and EHD friction/traction properties of the fluids will dominate the energy losses.