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A viscosity modifier solution to reconcile fuel economy and durability in diesel engines

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ABSTRACT

In this paper the design and architectural features of a new viscosity modifier (VM) with the optimal balance between fuel economy and durability are explored. The viscometric properties of the new VM and fuel economy performance are described and demonstrated in a range of diesel engines, both in passenger vehicles in the New European Driving Cycle (NEDC) and in a mid-size diesel engine under a variety of heavy duty driving conditions. In both FE tests, up to 2% fuel economy improvements were consistently observed for the lubricant oils formulated with the new FE VM. In addition, the durability in sooted environment is addressed which is now critical for both passenger car and heavy duty diesel oils, and the VM's role in soot-induced viscosity increase as related to both retained fuel efficiency and soot-induced wear is demonstrated. The new VM delivers additional control of soot-induced viscosity control in bench screening tests, where the oil viscosity was reduced by an order of magnitude at 9% soot loading condition. Furthermore, in both Peugeot DV6 and Mack T11 tests the kinematic viscosity of the highly sooted oils was reduced by more than 50% at the end of the tests after replacing the conventional VM with the new FE VM. Lastly, wear and durability performance is demonstrated in both engine screening tests and heavy duty engine tests, where the new FE VM helps maintain the low soot-induced wear and the outstanding engine cleanliness.

1. Introduction

With tightening of emission regulations due to environmental concerns, the requirements for vehicle fuel efficiency continue to increase. Meeting these requirements has been a challenging task for original equipment manufacturers (OEMs) leading to engine downsizing and introduction of new hardware to improve vehicle fuel efficiency. However, engine development usually requires large investment and long cycle time. A complimentary approach to gaining additional fuel efficiency is in designing lubricants to minimize frictional energy losses in the engine.

A common route to obtain fuel economy from the lubricant is to reduce its viscosity [1–5]. However this route leads to concerns about engine durability and wear protection expected from the lubricant. To optimize both parameters, fuel efficiency and wear, lubricant viscosity profiles have been developed using special Viscosity Modifiers (VM) [6–8]. In these cases viscosity is minimized at the range of temperatures characteristic of a typical driving cycle. However at the peak temperatures these special VMs are designed to provide the necessary viscosity boost to protect the engine. These enhanced lubricant viscosity profiles have been shown to result in improved fuel efficiency and excellent wear protection [6,7] in both gasoline and diesel engines.

However, the viscosity of the lubricant in-service is affected by many factors, including mechanical shear, fuel dilution, oxidation, and soot loading. Of these, oxidation and soot in the lubricant can result in viscosity increase and the loss of lubricant derived fuel economy [9]. Moreover, it has been shown in multiple studies that when soot in the lubricant is not properly dispersed it would not only result in viscosity increase but also in abrasive wear [10–17]. Multiple studies which included engine and field tests have shown the importance of good soot dispersancy for wear protection in both heavy duty diesel (HDD) as well as in passenger car diesel engines [18]. To address this, a number of tests to measure lubricant performance with respect to viscosity increase and soot-derived wear of the engine parts have been developed.

To prevent soot aggregation and thus viscosity increase and wear in diesel engines, either traditional dispersants or dispersant VMs, or both are used. It has been shown that some non-dispersant VMs containing aromatic functional groups can provide additional dispersancy to the engine lubricant [19,20]. The use of these VMs is especially relevant in lower viscosity oils where the use of high concentrations of traditional dispersants can be limited by viscometric constraints. Thus the development of a

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VM that can provide an optimal viscosity–temperature profile for fuel efficiency and have credits in soot-related viscosity increase and soot-induced abrasive wear, could be extremely useful in balancing fuel economy with diesel engine protection.

Yet another aspect of the VM performance in diesel engine oil is in its ability to minimize oil related deposits. In general, polymers can contribute to deposit formation in the engine, and the higher the concentration of the polymer, the more deposits are expected to form, provided the additive package is the same. Thus a low treat rate of the viscosity modifier in the engine lubricant is one of the keys to preventing deposit formation. This prevention of deposit formation [21] from the polymer can potentially enable lower treat of detergent and other deposit control additives. However, the polymer concentration is not the only parameter that affects lubricant-related deposit formation in the engine. The particular chemistry of the polymer plays a significant role.

In this paper, a VM polymer design that optimizes the lubricant viscosity–temperature profile to minimize the viscosity at in-service temperatures and to provide necessary viscosity at peak temperatures is presented. When using a lubricant with this VM, fuel economy improvement of up to 2% can be obtained in both passenger car and mid-size diesel engines. In addition, this VM can provide credits in soot-related viscosity increase in both passenger car and HDD engines, as well as play a role in soot-induced wear control. Finally, the low treat rate of this VM allows one to formulate the oil with good deposit control.

2. Viscosity modifier design

The hydrodynamic lubrication regime in modern diesel engines is characterized by a formation of continuous lubricant film between the surfaces. According to the Stribeck curve the frictional energy losses in the liquid film are significantly lower than in the solid to solid contact allowing the engine to operate more efficiently. Without direct contact of the surfaces the energy dissipation happens in the fluid film and is directly related to film viscosity. Thus the viscosity of the oil at operational temperatures plays a significant role in improving fuel economy performance in diesel engines. The viscosity modifier can be used to provide the ideal viscosity temperature profile for a lubricant to deliver fuel economy and wear protection at the same time. The ideal VM would deliver a viscosity–temperature profile that would maintain the viscosity at high peak temperatures to form sufficient oil film for engine protection and at the same time it would have lower viscosity at typical operating temperatures to reduce frictional energy losses and improve fuel economy.

A new VM based on hydrogenated styrene-diene (HSD) star chemistry was designed to provide an optimal viscometric behavior for fuel efficiency and durability [22]. The VM is able to expand at high temperature to have a high viscosity contribution to the oil and contract as temperature decreases to reduce its viscosity contribution at lower temperatures.

The viscosity–temperature relationship of this new VM is shown in Fig. 1, which plots the relative viscosity over a range of temperatures. Relative viscosity is calculated from the viscosity of the VM containing oil divided by the viscosity of the base oil. It describes the viscosity contribution attributable to the VM. For a conventional HSD VM, relative viscosity decreases as temperature increases, indicating that at low temperatures VM contributes more to viscosity in relative terms. For polymethacrylate (PMA) VM, relative viscosity increases with temperature. This is a unique behavior for PMA, as its coil size in the oil decreases as temperature decreases. The new FE HSD behaves similarly to PMA. As temperature decreases, the coil size and thus hydrodynamic volume of the new FE HSD VM decreases, leading to lower relative viscosity at low temperatures. The details of different VMs used in the study are summarized in Table 1.

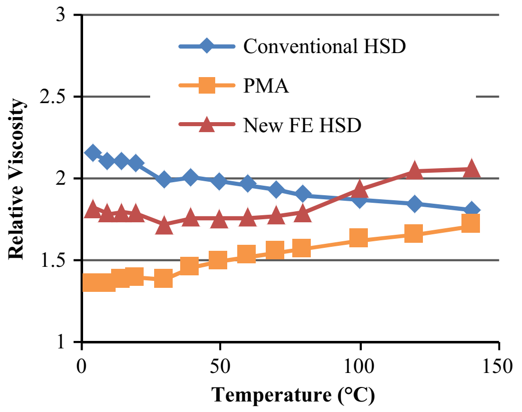

Fig. 1. Relative viscosity as a function of temperature for oils with conventional HSD, PMA, and new FE HSD.

Table 1
Structure and composition of the viscosity modifiers used in the study.

Name	Description	Architecture
Conventional HSD	Hydrogenated poly(styrene-diene)	Star
New FE HSD	Hydrogenated poly(styrene-diene)	Star
PMA	Polymethacrylate	Linear
FE PMA	Polymethacrylate	Comb

To assess the viscometric behavior of the VMs in the finished lubricant three oils were blended using the same mid-SAPS additive package in the same base oil. All oils were formulated to the same high temperature high shear viscosity (HTHS) at 150 °C (3.5 cP) and the HTHS at lower temperatures as well as kinematic viscosities (KV) at 100 °C and 40 °C were measured. It is believed that HTHS viscosity at 150 °C correlates with wear performance at peak temperatures while HTHS viscosity at lower temperatures can be indicative of the frictional losses and thus fuel efficiency in the operational temperature range. As shown in Table 2, the oils formulated with different VMs to the same HTHS at 150 °C exhibited different viscosities at lower temperatures. Both the new FE HSD and the FE PMA have significantly lower HTHS at 100, 70 and 45 °C compared to the conventional HSD. The low HTHS is expected to contribute to fuel economy credit in the engine.

It is also worth noting that to achieve the same viscosity, FE PMA requires almost three times of the solid VM compared to HSD (both conventional and the new FE VM). The high polymer treat rate could be a potential debit in some aspects of engine performance such as deposit formation, and thus is not desirable.

3. Fuel economy performance

3.1. Fuel economy measurements in the New European Driving Cycle (NEDC)

The fuel economy performance of the new FE HSD was first demonstrated in the NEDC using various diesel engine passenger vehicles. The NEDC is designed to evaluate the emission levels, or fuel economy, of passenger cars in Europe. As shown in Fig. 2, the entire cycle takes 1180 s, and is composed of urban driving stages from 0 to 780 s and a highway driving stage from 781 to 1180 s. The cycle starts at room temperature (typically 22 °C) and ends in