Fuel economy considerations: Effect of lube oils and their volatility

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The concept of friction has quite literally sparked the fire of humanity's progress; yet, in an ironic twist, the very same progress is impossible without reducing friction as much as possible. The automotive industry currently faces the struggle of both improving fuel economy and reducing emissions, due to regulations such as the Safe Affordable Fuel-Efficient (SAFE) Vehicles Rules. Such regulations came about to improve the quality of the environment and lay down strict deadlines. As such, the automotive industry has developed lower viscosity lubricating oils, among many improvements, which reduce friction in engines allowing even legacy models to benefit. Even though low viscosity oils improve fuel economy by approximately 1% with viscosity grade, reducing the viscosity of engine oils can increase wear as well as friction under certain conditions. Thus, it is vital to properly analyse all facets of low viscosity engine oil to acknowledge the deficits together with the benefits when devising a strategy to further develop environmentally benign automobiles.

The effects of lubricating oils vary widely with the lubrication regimes: boundary lubrication, mixed lubrication, as well as hydrodynamic lubrication and elastohydrodynamic lubrication. Each lubrication regime depends directly on the oil film thickness of any lubricating oil and surface-to-surface contact between two sliding surfaces. The main method low viscosity engine oils employ to improve fuel economy is reducing viscous drag during hydrodynamic or elastohydrodynamic lubrication conditions, where the film thickness of the lubricant is large enough to completely separate the two sliding surfaces, removing any surface-to-surface contact. The main deficit of low viscosity engine oils is that they are more inclined to shear thinning at high temperatures and thicken less at lower or starting temperatures than a counterpart engine oil of higher viscosity; both of these factors cause the lubricating film thickness to decrease. With decreasing film thickness, the lubricating regime shifts towards mixed and boundary lubrication, of which the latter defines a lubricating system where the oil film thickness cannot overcome the surface roughness and the former defines the transition state between boundary and hydrodynamic lubrication with a film thickness that overcomes some but not all of the surface roughness.

In addition to the film thickness decrease is the fact that the 100°C viscosity typically has an inverse relationship to the base oil volatility. As the viscosity is reduced to benefit the energy efficiency via a reduction in friction and viscous drag, the volatility of the oil may contribute to oil loss through volatilisation. Volatility determines how much of the oil will evaporate at very high temperatures, and then how much more oil will be consumed as a result. If the volatility is low, the maximum amount of oil can stay in the engine for a longer amount of time and the oil will keep its ideal viscosity for longer. When oil loss occurs, there will likely be a resultant viscosity increase

in the remaining oil in the sump, thereby negating the idea of reducing the oil viscosity and also raising concerns regarding stay-in-grade issues.
To mitigate this, it is necessary to use base oils and blend components that have excellent volatility properties, thereby minimising the concern. A very useful test for volatility is called the Noack Volatility Test, also known as ASTM D5800. Figure 1 indicates that any volatility higher than 15% is too high and will most likely not pass crucial oxidation tests, including the IIIG engine test, and may not meet required API oil guidelines [1]. In addition to the API guideline, both General Motors and the European Automobile Manufacturer's Association (ACEA) have their own specification that sets the maximum Noack volatility at 13% [2]. Another important note is that the volatility of engine oils has been found to be lower than the volatility of their base oils, in general. Thus, it is standard in Europe to have the Noack volatility of a base oil rated at 2% higher than the engine oil [3].

Volatility, mass % loss, 1 hr, @ 250°C (ASTM D5800)

Figure 1: *A display of the Noack volatility characteristics determined by ASTM D5800 [1]*

Some potential solutions could involve the use of polyalphaolefins (PAOs) or esters in the base oil blend. Of particular note are the dodecene based PAOs, which offer exceptional Noack volatilities. The volatility of an oil is most often driven by the lightest molecular weight portion of the base oil blend. As an example, some dodecane-based PAOs contain a 36-carbon atom component (dodecene trimer) as the lightest material. This is typically 6 carbon atoms heavier than the traditional decene-based PAO. The end result of this change is a large decrease in the Noack volatility to about 5.5%, which is much lower than the typical 13 to 14% Noack volatility of a 4 cSt PAO or Group III.

Low viscosity esters are also a potential solution since the ester moiety could form a dimer with itself, effectively doubling the molecular weight of the material resulting in low measured volatilities under the Noack testing conditions. It has been proposed in a recent study that Group V base oils (esters) can be formed by a pathway that starts with methylenealkanes, which are byproducts from the formation of Group IV base oils. The esters analysed in the study had dynamic viscosities ranging from around 5 Pa·s to around 0.001 Pa·s as the temperature increased from -50°C to 150°C. They noted, however, that only esters derived from an oct-1-ene dimer could serve as potential Group V base oils because the other esters could reach an undesirable volatility at certain temperatures [4]. Esters also have the advantage of aiding additive solubility as well as elastomer seal swell to counteract seal shrinking that may be present in Group III and IV base oils. Blending options with these and other materials can provide a means to low-viscosity and low-volatility options for engine oils. The trick seems to be in the components and skill of the formulators that take advantage of these properties.

Many past studies such as that of H. A. Everett [5] have already correlated an increase in friction and wear with reducing kinematic viscosity, further defining the increase in friction and wear as the result of a decreasing lubricating film thickness.
To understand the effects of low-viscosity engine oils on wear, Carden and his team utilised a heavy-duty truck engine and subjected it various conditions and lubricants. A total of 3 test oils were utilised in a IVECO Cursor 13 Euro V engine: a baseline 5W-30 oil with a kinematic viscosity of 12.28 mm2s-1 at 100°C, a very low viscosity oil with a kinematic viscosity of 6.53 mm2s-1 at 100°C, and a ultra-low viscosity oil with a kinematic viscosity of 4.82 mm2s-1 at 100°C.

On-line wear testing of the engine showed that the baseline oil had the least wear and the reduction of viscosity directly correlated to an increase in wear; particularly the top piston rings of the engine showed the greatest increase in wear to a reduction in oil viscosity. It must be noted that heavy-duty vehicles utilise a higher viscosity grade than is seen for passenger vehicles due to greater load conditions.
The typical engine oil grade for heavy duty vehicles ranges from SAE 5W-40 to SAE 15W-40, while it is SAE 5W-30 for passenger vehicles as mentioned previously.

Micro-pitting is an issue that can arise in bearings when the lubrication film thickness gets significantly small. This is one of the consequences of having an ultra-low viscosity. ZnDTP additives were deemed one of the main causes of micro-pitting despite protecting against wear [7]. It is possible to reduce micro-pitting by reducing ZnDTP additive concentrations or lowering the viscosity of the engine oil; however, this action leads to wear. Fortunately, introducing PAO oil into the oil blend and the addition of friction modifiers (FM) to oils containing ZnDTP reduces the tendency towards micro-pitting by reducing local stresses near the surfaces via lowered friction [8,9].

Despite the improvements shown by roller crankshaft bearings, it is not feasible to replace all the positions in an engine with roller bearings as the durability of the engine decreases and the issue of micro-pitting and wear increases. Nonetheless, efforts have been made to mitigate wear despite the necessity to decrease viscosity for environmental goals and targets. Most notably the proper utilisation of additives allows for tremendous synergies between the benefits of low viscosity oils during hydrodynamic lubrication and additives such as friction modifiers that improve friction during boundary and mixed lubrication.

Currently, the most utilised method for improving low viscosity engine oils is the addition of FMs due to their cost-effectiveness. FMs are usually formulated using amphipathic molecules that have a polar portion, which interacts with metal surfaces, and a hydrocarbon portion, which allows other materials to slide across. The polar segments usually contain groups such as carboxylic acids or the metal molybdenum [10]. Yamamoto studied three FMs: Molybdenum dialkylthiocarbamate (MoDTC), Glyceryl Mono-Oleate (GMO), and a Polymer type friction modifier (PFM) for use in ultra-low viscosity engine oils.

The tribological characteristics of 0W-16 engine oils with each FM as well as one oil formulation with no FM were studied utilising a cylinder on disk friction test with a load of 200 N and a testing time of 15 minutes as well as a sliding rolling type friction test with a load of 30 N, a mean rolling speed of 0.01 to 3 m/s, and a slide-roll ratio of 50%. Afterwards, each tribofilm generated was tested with a ball on disk friction test with a load of 2.0 N, a stroke of 5 mm, and a sliding speed of 1 mm/s. The cylinder on disk test results showed a friction coefficient of 0.05 for MoDTC, 0.10 for GMO, 0.13 for PFM, and 0.15 for the oil without FMs. The sliding rolling type friction test showed that the friction coefficient of the MoDTC oil formula decreased with oil aging and the friction coefficient of the oil formula without FMs increased with oil aging; yet, the PFM and GMO oil formulas showed negligible change. Comparing the results of the ball on disk friction test of the tribofilms, the tribofilm generated from the MoDTC oil formula had the lowest coefficient of friction. Due to these observations, MoDTC was chosen as the most effective FM from the study in reducing friction and wear during boundary lubrication.

Conclusion

Engine oils have entered a phase of continuously decreasing their viscosities, yet the problem of friction and wear still remains. As oil viscosity decreases, so too does lubricating film thickness. The thinning of lubricating films has the potential to cause increasing amounts of damage within any given engine due to the reduced lubricating action. In order to combat these concerns, researchers have continuously developed additives that improve upon the low viscosity engine oil's deficits. For instance, FMs have allowed for great improvements during boundary lubrication and decreasing wear, notably MoDTC has shown significant reduction in friction compared to its competitors.

For the betterment of the environment, regulations will continue to grow and technology will advance, but it is vital that research of friction and wear continues so that we may not neglect their underlying risks.

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