THERMAL CHARACTERISTICS OF NEW AND USED DIESEL ENGINE OILS

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SUMMARY

Used diesel engine oils were found to have increased thermal conductivity in comparison to new oil. The magnitude of the effect is dependent on the concentration, size and dispersion of soot particles, as well as the oil composition. While soot in the engine oil is generally deleterious to engine performance for wear and deposits, no negative effects on thermal performance of the oil itself, indeed even slight positive effects are expected, for oils which maintain soot in stable dispersion. The relevance of this finding to thermal control in modern diesel engines is briefly discussed.

Keywords: Thermal Characteristics, Diesel Engine Oil, Used Oil, Soot

1 INTRODUCTION

Diesel engines today are evolving rapidly in response to environmental legislation and the continuing demand from users for more horsepower/litre engine size and better fuel efficiency. As a result, diesel engine oils will be called on in 2002 to handle an increased thermal load and a significantly increased soot load resulting from exhaust gas recirculation (EGR). While as recently as several years ago, the concentration of soot in a typical used engine oil at drain from a line haul operation would have been on the order of 0.5 to 1% by weight, we have seen it increase post 1998, due to retarded fuel injection timing, to a level of typically 2-4% in comparable operations. In 2002 when the standard of 2 grams/bhp-hr for oxides of nitrogen comes into effect, concentrations exceeding 5% may be realized. Indeed, the Cummins M11 engine test for the future PC-9 oil category will be rated at an 8.5% soot level, Wang et al. [1]. These circumstances raise the question – how will increased levels of soot impact the performance of engine oil?

Of course the deleterious effects of soot are well known. For example, McGeehan et al. [2] reported various effects of soot in a Cummins M11 engine, including low temperature oil thickening, increased sludge, increased pressure drop across the oil filter, and valve train wear. Van Dam et al. [3] reported increased valve train wear in the Cummins M11 and increased cylinder liner wear in the Mack T-9 engine tests. Bardasz et al. [4-9] have reported that oil viscosity growth, another undesirable characteristic, varies with engine type, operation, fuel, and oil formula. They have shown, as have others [10], that the primary soot particles found in diesel engine oils are fused aggregates of smaller particles which form “rods with branches” with to best approximation an ellipsoidal shape. They have concluded that soot particle sizes are primarily controlled by the engine type and operating conditions. Further, they found that soot mitigated oil viscosity increase was a function of both soot size and amount, and developed a correlation between oil viscosity rise and total particle surface area. Oil dispersancy was found to influence long-term soot stability and engine wear related to soot agglomeration [5,7]. In spite of all these previous studies on the effects of soot, nothing has been published to our knowledge on the effect of soot on the thermal properties of the oil.

There should be greater interest in the thermal properties of engine oil because future engine temperatures are projected to go higher, with thermal loading being more of a problem. There is also another interesting reason to study the soot in engine oil dispersion, in light of recent findings that dispersions of nanosize particles in liquids can significantly impact thermal characteristics of the fluid, Choi et al. [11]. From our point of view, soot laden diesel oil is a colloidal system with some value as a model for such nanofluids, even though soot particles are on average 10 to 100 times the size of nanoparticles.

2 EXPERIMENTAL

Three test oils, named red, white, and blue, were used in the test program, Table 1. The red oil was a high quality 15W-40 CH-4 heavy duty diesel engine oil with proven field performance and formulated with conventional mineral (API Group I) base oils. The white and blue oils were 5W-40, CH-4 oils formulated with detergent-dispersant additive chemistry similar to the additive in the red oil, but with a higher base number. The white oil used a synthetic (API Group III) base oil, while the blue oil used a polyalphaolefin (API Group IV) base oil. The synthetic oils were lower in viscosity at low temperature than the mineral oil, and the polyalphaolefin is known to have slightly higher thermal conductivity than either Group I mineral oils or Group III synthetics derived from mineral oil. The three test oils were studied in a severe on-road line haul application in Cummins Signature series engines. The white and blue oils were in the engine significantly longer (> 50%) than the red oil before drain. All oils were studied for multiple drains...
for a total of more than 300,000 miles of engine use. Each oil was studied in five different trucks. Samples of the oil were tested new, and at various mileage intervals until drain. The intervals were chosen to obtain samples with significantly varying soot levels.

<table>
<thead>
<tr>
<th>SAE Grade</th>
<th>Red</th>
<th>White</th>
<th>Blue</th>
</tr>
</thead>
<tbody>
<tr>
<td>15W-40</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>15W-40</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Base Oil</td>
<td>MO*</td>
<td>SynMO*</td>
<td>PAO**</td>
</tr>
<tr>
<td>Additive</td>
<td>A</td>
<td>A+B</td>
<td>A+B</td>
</tr>
<tr>
<td>Viscosity at 40°C (cSt)</td>
<td>110.86</td>
<td>85.1</td>
<td>86.8</td>
</tr>
<tr>
<td>Density at 40°C (g/cm³)</td>
<td>0.8684</td>
<td>0.8422</td>
<td>0.8452</td>
</tr>
<tr>
<td>Thermal Conductivity at 40°C (W/m·K)</td>
<td>0.1321</td>
<td>0.1364</td>
<td>0.143</td>
</tr>
</tbody>
</table>

Table 1. Fleet test oils for thermal characteristics study

* Mineral oil
** Synthetic mineral oil
*** Polyalphaolefin
A Additive package, total base number 10.1
A+B Detergent boosted A, total base number 11.5

The thermal conductivity, density, heat capacity, and viscosity at 40°C and 100°C, and percent soot by weight was determined for each oil sample, along with many other chemical and physical tests traditionally run on engine oils. Selected samples were also studied to determine soot size and dispersancy. Engine inspections at the end of the test indicated good performance and no abnormal conditions for either the oils or the engines during the test.

Thermal conductivity was determined by the transient hot-wire method previously described by Lee et al. [12]. In this method power is applied briefly to an insulated platinum wire suspended in the fluid being tested. The wire serves as both the heating element and the thermometer. The prior work described by Lee et al. established that thermal conductivity results for water and ethylene glycol in this apparatus matched those published in the literature with a maximum error of 1.5%.

Heat capacity was determined by modulated differential scanning calorimetry. Heat capacities were measured at selected temperatures ranging from -20°C to 150°C, and an equation for heat capacity as a function of temperature was developed using a simple polynomial regression.

Soot percentage was determined using both Fourier transform infrared and thermogravimetric analysis (TGA) methods common in the industry for soot analysis. Soot size was determined by scanning electron microscopy.

3 RESULTS AND DISCUSSION

Soot buildup in the oils was surprisingly high, as much as 7.5% in some engines at extended oil mileage, Figure 1.

Figure 1. Percentage soot plotted against sample mileage of the fleet test oils

Soot levels climbed particularly for the blue and white oils as they aged well past the mileage where red oils were changed. The amount of soot trapped in the oil increased as both a function of the mileage on the oil as well as miles on the engine, with a correlation on the order of $R^2=0.8$ provided the data is restricted to a particular engine. The effect of engine miles is due to increase in piston ring gaps as the engine wears with age, thereby allowing increased blowby of combustion gas into the engine oil. This surmise was confirmed by tear-down and inspection of six of the engines. Typical ring gap increase from the new condition maximum service specification was 150% for the oil ring and 10 to 20% for compression rings. This wear level was a characteristic of the particular ring arrangement and hardware used in the test.

Given the large amounts of soot in the oil, it was not surprising to find a change in the oil thermal characteristics. Thermal conductivity, $k$, increased by as much as 15%, Figure 2. However, it was also noted that the slope of thermal conductivity versus temperature was greater for oil without soot. Heat capacity, $C_p$, on the other hand was not greatly affected, Figures 3. For the mineral oils, changes in heat capacity due to soot are generally within experimental repeatability, ±1.5%. At 40°C, they are also within 5% of the values calculated from a general equation for hydrocarbons [13]. For the polyalphaolefin oil, the change is slightly greater, indicating a slight decrease in heat capacity due to soot. This would be logical since the heat capacity of soot is lower than oil.

The response of the mineral oil based - red oil and the synthetic mineral oil – white oil, to soot is similar, although the white oil has a higher level (about 4%) of thermal conductivity both new and over the range of soot concentration. The polyalphaolefin synthetic (blue)
oil has a new oil thermal conductivity 8.5% greater than the red oil and 5% greater than the white oil, but it has a lower response to dissolved soot, initially. In fact, at soot amounts around 2 weight percent the white oil thermal conductivity approaches that of the blue oil, and their thermal conductivity curves then appear to remain within a few percent of each other up to 4-5% soot level, Figure 4. This result suggests that the oil with the best thermal characteristics when new, may not retain the same degree of advantage as the oil ages. Furthermore, the used oils have somewhat better thermal characteristics than their respective new oils.

The increase in thermal conductivity caused by colloidal spheres in liquids has been previously modeled, for somewhat larger particles than diesel engine soot,
Arguing against this idea is the work of Kornbrekke et al. [9] showing that dispersed carbon black in solvent showed increased electrical conductivity, which they associated with a double layer effect, which also increased viscosity and one might suppose could likewise influence thermal conductivity. Following their work, we also dispersed the same carbon black in new test oils and measured thermal conductivity. The results are shown in Figure 7, confirming the expected rise in thermal conductivity. Some of the white oil data suggests there may have been poor dispersion of the carbon black in some samples. This does not mean that dispersed metals do not also contribute to the overall electrical and thermal conductivity of the oils, but the metals are present at two orders of magnitude lower concentrations, less than 0.03 wt %.

As has been mentioned, it is also well known that the amount and size of soot influences oil thickening [4-9, 15]. There will be a potential trade-off between improved thermal conductivity and reduced pumping rates of thickened oils. Indeed, severely thickened oils may cause pumping failures, particularly at low temperatures. The relationships among thermal conductivity, viscosity, and % soot were briefly investigated. As expected, Figure 8 shows that in general, higher soot percentages cause oil viscosity increase. However, there is a considerable range of viscosity for the same level of soot. Furthermore, oils at the same viscosity differed significantly in thermal conductivity.
White and blue oils had higher thermal conductivity than the red oil when compared at like viscosity. For each of the three oils, the viscosity increase and the thermal conductivity increase, $k/k_0$, where $k_0$ is the thermal conductivity of the new oil, could be correlated with the amount of soot in the oil (viscosity $R^2 = 0.7$) or thermal conductivity ($R^2 = 0.8$), Figure 9. For the viscosity, Bardasz et al. [4] reported an effect of base oil type, with more paraffinic API Group II oils apparently having less soot interaction, i.e. a lower “apparent soot volume”, and therefore less viscosity increase than Group I oils. We noted that the most paraffinic of our three test oils had lower initial thermal conductivity increase and at first thought this might be related to the phenomena described by Bardasz et al. However, the same oil showed a small viscosity decrease during the initial use period which may be related to the lower thermal conductivity measured. We attributed this to shear thinning of the oil that is not countered by as much soot induced thickening as with the other two oils. Once this shear thinning period was past, the oils behaved similarly with respect to thermal conductivity increase.

To better understand the impact of soot on the overall capability of engine oil to transfer heat, we predicted the heat transfer coefficient of the new and used oils at 40°C. We had previously measured heat transfer coefficients in a heat transfer loop at Argonne National Laboratory for both water and oil based fluids in mixed to laminar flow. An equation was derived from this work to predict the heat transfer coefficient in the loop as a function of Reynolds and Prandtl numbers. (The Reynolds number is defined as $DVp/u$, where $D$ is the tube diameter in cm, $V$ is the velocity of flow in the tube in cm/s, $p$ is the fluid density in g/cm³, and $u$ is the fluid viscosity in poise. The Prandtl number is $Cp/k$, where $C$ is the heat capacity in kJ/kg·K and $k$ is the thermal conductivity in W/m·K). By measuring the required properties to calculate the values of these dimensionless groups some idea is achieved of relative heat transfer coefficients for the new and used oils, Figure 10. Looking at the oils this way predicts a small improvement in heat transfer coefficient for the 5W-40 viscosity grade versus the 15W-40 traditional grade, which is further accentuated in the used, soot-containing oil. Similarly, the dimensionless groups can be used to predict heat transfer coefficients in other situations that have been correlated in this fashion.

Engines equipped with cooled EGR systems will transfer additional heat to the coolant as the EGR cooler removes heat from the recirculated exhaust gas. Higher coolant temperature will lead to higher oil temperature. At the same time, heat transfer properties of the oil will change due to increasing amounts of soot produced in an EGR engine. Comparing the non-EGR to the EGR case for a specific engine; in the non-EGR case at a rated condition of 600 hp and 1800 rpm, the oil rifle temperature was 95.5°C and the oil pan temperature was 103.3°C. By adding the EGR system to drop the emissions to below 2.5 g NOx, the oil rifle temperature is 106.1°C and the oil pan temperature is 113.3°C if the cooling capacity is unchanged. However, if the oil is formulated to keep soot in stable suspension, the cooling capability of the oil will increase with time, so that temperatures should drop as soot concentration increases, absent any other unanticipated effects, e.g. buildup of deposits. As an example, we estimated the change in predicted heat transfer coefficient for the white oil at a 15% increase in thermal conductivity to be around 5% (using the previously determined Reynolds # and Prandtl # relationship). We assume that the heat input into the oil from the engine is insensitive to changes in oil thermal conductivity, since most of the heat from the engine is...
going into the exhaust stream and into the coolant. One can easily be convinced about the correctness of this assumption by conducting a simple network analysis e.g. as given in reference [16]. The heat output to ambient under the hood conditions, however, is sensitive to the oil thermal conductivity. Thus heat output for case 1 with no soot buildup, is equivalent to case 2 with soot 4-5 % and thermal conductivity increase of 15%, heat transfer coefficient increase of 5%. Therefore;

\[
\text{Heat Output from oil} = h \times A \times \Delta T,
\]

where \( h \) is the heat transfer coefficient, \( A \) is the area of heat transfer, and \( \Delta T \) is the temperature difference between the oil and the ambient under the hood temperature. Setting case 1 equal to case 2 and rearranging terms;

\[
\Delta T_2 = \Delta T_1 \times \frac{h_1}{(1.05 \times h_1)}
\]

where 1 and 2 refer to the two cases, and \( h_2 = 1.05 \times h_1 \), a 5% increase. This predicts that oil temperature should be 5% closer to ambient temperature for case two, or going back to our original case with EGR, one might expect a drop in the oil pan temperature from 113.3°C to 109.7°C, with an under hood temperature of 49°C. Given the strong increase in oil degradation rate with temperature, even this small temperature change could be significant.

4 CONCLUSIONS
This work has shown that the heat transfer of used diesel engine oils is not adversely, but rather positively impacted by high levels of soot, at least until the soot particles aggregate to form significantly larger particles. Therefore, the main thermal challenge for high soot-containing diesel oils is to keep the soot well dispersed in small particles and to prevent carbonaceous deposits on metal surfaces. Different oil formulations can be formulated to maximize heat transfer coefficient. The importance of the improvements in oil heat transfer coefficients that can be achieved is significant.

5 REFERENCES