

Soot Removal from Diesel Engine Lubrication Systems

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ABSTRACT

The removal of soot in the lubricating sumps of diesel engines is a formidable task, further compounded by the introduction of Exhaust Gas Recirculation (EGR). Efficient removal of soot would help ensure engine durability and engine performance while increasing oil drain intervals thus reducing maintenance costs. This paper describes a method by which soot can be separated from the oil with the application of an electric field by utilizing the small electrical charge on the soot particles. The electric field is applied to a network of electrodes that support an open porous network which stabilizes the weakly bound soot cake. Significantly higher filtration efficiency was achieved as compared to mechanical particulate filtration and centrifugation. The paper also discusses the controlling conditions while detailing the performance testing at both a bench scale level and pilot scale level.

BRIEF OVERVIEW OF SOOT

Early in the widespread use of the internal combustion engines, it was considered important to be able remove harmful particulates from the lubricating fluid. These contaminating particulates were thought to increase wear and shorten the life of the engine and its moving parts. The contaminants which cause wear and form insoluble components are managed partially by the oil's additive package.¹ Some of these contaminants result from blow-by of combustion byproducts from the fuel or lubricant, particles from the outside air which pass through the air intake system, and degradation of the oil. A mechanical filtration of these contaminants has been a standard part of larger internal combustion engines, both spark ignition and compression ignition. It has been a challenge to manage soot generation in compression ignition engines through conventional mechanical filtration due to the small size of the particles.

Dispersants within the lubricant additive package are effective in keeping the soot particles from agglomerating and forming larger particles which are typically responsible for wear. However, when the dispersant becomes depleted due to soot loading, the soot agglomerates grow quickly and have a negative effect on the lubricant's viscosity and useful life of the lubricant. The engine type, age and operating conditions of the engine will sometimes create a "soot challenged" condition in which soot management becomes a limiting parameter in the useful life of the lubricant. Various separation approaches have been employed in an active particle management strategy, ranging from higher efficiency single-pass filtration to finer filtration through the use of by-pass filtration to centrifugation. This study will attempt to compare three approaches: mechanical filtration, centrifugal filtration and electro-agglomeration, for soot removal in diesel engines. Electro-agglomeration is a relatively new application for a separation mechanism that is widely used in other areas.

CURRENT ALTERNATIVES

There are multiple options in the market currently that claim to provide effective protection from soot.^{2,3,4} These include, cellulose/synthetic media filters, centrifuges and depth filtration devices. The media filters effectiveness is based on the mean pore size of the media being small enough to filter soot. Centrifugal separation process relies on the density differences between the oil and the soot to separate the soot from the oil. However, our evaluations have shown that these tools have minimal effectiveness when the soot is in the un-agglomerated state, as shown in [Figure 1](#). The testing showed that they were less than 20% efficient in removing un-agglomerated soot over an extended period of testing. The issue with media filtration is that the un-agglomerated soot particle size is in the nanometer 'range' and the pore sizes in the media are not small enough to filter soot. In cases where

the media pore size is small enough to filter soot, the pressure drop across the media is too high for the application. Also, the media filters do not possess enough capacity to hold the amount of soot that is in the oil. In the case of centrifugation, the devices demonstrated high levels of oil turbulence that would prevent soot from being removed at a speed achieved by the units.

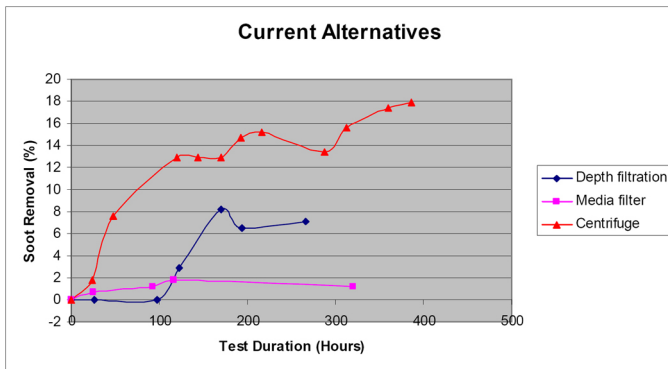


Figure 1. Effectiveness of current alternatives

ELECTRO-AGGLOMERATION MECHANISM

Application of an electric field to facilitate separation of particles, colloids and molecules within a fluid has been practiced in many applications for many years.^{5,6} Most finely divided particles which are suspended in a fluid possess a charge, albeit feeble in some cases. This charge is due to the intrinsic nature of the material and/or the result of charged sorbates in the fluid binding to the surface of the material. The net electrical charge on the particle, as in the case of colloids, results from the sum of charge on the particle as well the loosely held counter-ions, thus producing an ionic-double layer or Helmholtz-double layer. Diesel-derived soot contains polar functional groups on its surface due to incomplete combustion. In addition, elements from the oil additives such as sulfur, calcium, zinc and phosphorous are also bound to the surface of the soot particles. Additionally, oil additives which bind to soot and keep it dispersed also contribute to charge on this complex. Because of this net charge imbalance, a particle will migrate in an electric field to the electrode with the opposite charge and thus will be collected from the medium. When the charge on the particle, its zeta potential, is very small, the electric field necessary to bring about a migration and ultimate separation becomes very high. In some cases the field is beyond the breakdown voltage of the medium in which the separation is taking place, thus making it unattainable. Soot within a lubricating oil matrix exhibits a very small but non-zero charge, as evidenced by its ability to migrate to a positive electrode through the application of a high-voltage DC electric field. Attempts to measure and quantify the zeta potential of the

soot particles within an undiluted oil matrix have been less than adequate. This is due to the physical properties of the fluid, including color and opacity. These factors affect conventional zeta potential determination using techniques such as electrophoretic mobility with laser light scattering detection.

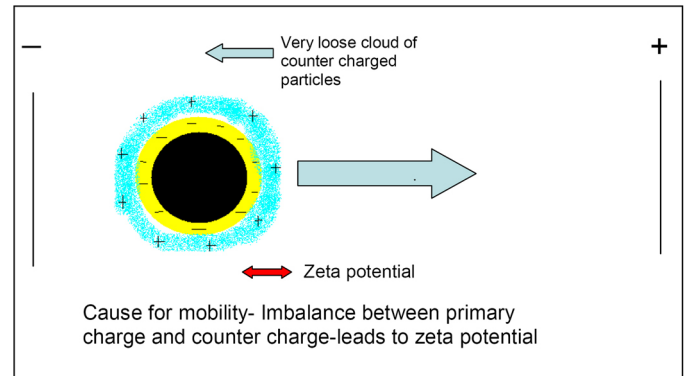


Figure 2. Electrophoresis Transport Phenomena

EXPERIMENTAL METHODS

Small Scale Electro-agglomeration Test Cell

Two electrodes were placed into a 400 ml beaker, separated by a distance of approximately 1.5 cm. Both the anode and cathode electrodes were made of fine mesh stainless steel screen, 60 × 60 mesh, approximately 1 cm by 2.7 cm in size. These electrodes were attached to platinum wire and then to the power supply. The electrodes were positioned in a parallel configuration within the test cell. The test cell was placed on a magnetic stirrer/hot plate which was used to maintain temperature and sample mixing when required. Temperature in the test cell was measured using a thermometer and recorded. In a typical test run the oil was diluted to 2 wt % soot using fresh oil as the diluent. This mixture was added to the test cell until the electrodes were completely covered. The temperature of the mixture was raised to the specified operating temperature before the voltage was applied. In some cases electro-agglomeration experiments were performed using a static system while other experiments were performed with stirring or flow incorporated into the experiment. Flow was generated using a recirculating pump to simulate the proportional flow which might be experienced in a working engine, typically 10 cc/min (0.2 turns/min).

A Hipotronics HD125 high-voltage DC power supply was used in all the experiments. It is a variable voltage/current controlled power supply which could develop a maximum DC voltage of 25,000 volts. However in most experiments the voltages were in the 5-10 kV range. Current draw was also measured during the course of each experiment.

During the course of an experiment, samples of the oil were measured for their soot level and compared to the initial soot level of the oil. After an experiment the electrodes were withdrawn from the test cell and the soot cake was removed mechanically from the working electrode. The total soot cake was weighed and its soot level measured by the TGA procedure, described under Analytical Procedures.

A multifactorial DOE (design of experiments) study was conducted which involved the distance of electrodes, size of the electrodes, type of electrode, material composition of the electrode, and geometry of the noncollecting electrode as related to soot cake formation. In these experiments the small test cell as described above was used.

Reagents and Test Fluids

Various used and fresh oils were used in the electro-agglomeration experiments. The used oils were collected from engines in test cells, typically from Mack T-11 or Mack T-12 engine lubricant tests, or from engines used in heavy-duty field tests. A range of soot levels were used in the testing from relatively new oils with little or no soot to heavily sooted oils containing soot levels in excess of 6%. Soot levels were kept below 2 wt% by dilution with fresh lube oil for several reasons. Frequently, in oils containing soot levels significantly greater than 5%, the conductivity of the oil was too high and exceeded the breakdown potential, resulting in power supply shutdown. The use of intermediate soot level also is more in keeping with the objective of this device- namely to remove the soot as it builds up in the lube oil and well before the soot level reaches the critical stage. The fresh oils used for dilution were those typically specified by the engine manufacturer for heavy duty diesel engines, typically developmental PC-10 oil (now API CJ-4) in early work or API CJ-4 oils.

Analytical Procedures

Soot Analysis

A slight modification to the ASTM D 5967-05 (Thermogravimetric Analysis, TGA) method was used to analyze the soot content of all the oil samples and soot mat samples described in this paper. All soot level measurements described in the paper represent weight-percent soot.

Using a higher final temperature than specified in the ASTM D 5967-05 method allowed us to obtain the ash content in addition to the soot level. This modification called for running the temperature program to 1000 C rather than the 750 C specified.

The sample size was also reduced to 1 mL or less in order to minimize the amount of oil removed from the scaled down electro-agglomeration test cell. This is an important consideration in studies calling for successive sampling over

a period of time from the same cell. Collected samples were mixed and resuspended prior to transfer into the TGA pan.

All work was done on a Q500 TGS (TA Instruments) - equipped with an EGA Furnace. The following conditions were employed for each analysis;

Analysis Conditions

1. Select Gas: 1 (Nitrogen)
 2. Data storage: Off
 3. Equilibrate at 50.00°C
 4. Data storage: On
 5. Isothermal for 1.00 min
 6. Equilibrate at 650.00°C
 7. Isothermal for 1.00 min
 8. Select Gas: 2 (Oxygen)
 9. Ramp 20.00°C/min to 1000.00°C
 10. Isothermal for 5.00 min
 11. Select Gas: 1 (Nitrogen)
- Balance MFC: 10 ml/min nitrogen

Sample MFC: 90 ml/min of nitrogen initially

Data Sampling Rate: 5 sec/pt

Post Test Cooling: 30 min

The soot level was calculated by measuring the weight change from a flat portion of the trace prior to switching to the oxygen atmosphere (~650°C) and after the curve flattened out (~ 750°C). Dividing by the original weight of the sample yielded the percentage of soot in the sample.

Oil Quality

Analysis of all oil samples for standard oil quality measurements were performed at Southwest Research Institute or CTC Analytical Services.

INITIAL TRIALS

Figure 3 shows the time course of soot removal from oil containing a high level of soot. The oil was obtained from the sump of a heavy duty diesel engine following completion of a Mack T-11 test. Also shown in Figure 3 is the measured current in the test oil over the 8 hour duration of this study. The initial soot level of the undiluted oil sample was 6.51 weight %. Small oil samples, 0.25 mL, were removed from the test oil periodically and the soot levels were determined as described in the Experimental Section. Soot levels in the