

Effects of Oil Formulation, Oil Separator, and Engine Speed and Load on the Particle Size, Chemistry, and Morphology of Diesel Crankcase Aerosols

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ABSTRACT

The recirculation of gases from the crankcase and valvetrain can potentially lead to the entrainment of lubricant in the form of aerosols or mists. As boost pressures increase, the blow-by flow through both the crankcase and the valve cover increases. The resulting lubricant can then become part of the intake charge, potentially leading to fouling of intake components such as the intercooler and the turbocharger. The entrained aerosol which can contain the lubricant and soot may or may not have the same composition as the bulk lubricant. The complex aerodynamic processes that lead to entrainment can strip out heavy components or volatilize light components. Similarly, the physical size and numbers of aerosol particles can be dependent upon the lubricant formulation and engine speed and load. For instance, high rpm and load may increase not only the flow of gases but the amount of lubricant aerosol. In this study, the number, size distribution, composition, and morphology of entrained lubricant aerosol is examined on a medium-duty diesel engine operating at different speeds and loads. A unique sampling apparatus is described for sampling the aerosol in the same manner that it enters the intake. In addition, the performance of oil separators is examined. Results demonstrate that the size distribution changes with load, and contains both a sub-micron and super-micron component. The chemical composition of the aerosol varies depending on engine speed and load and oil separator used, while TEM results show that aerosol morphology changes with lubricant viscosity and also engine conditions.

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INTRODUCTION

Leakage of gases from the combustion chamber past the piston rings is often referred to as blowby. These gases pass into the engine crankcase, where they are vented to prevent excessive pressurization. Leakage may also occur from the cylinders past the valve guide seals into the areas contained by the valve covers. For many years, engine blowby gases were simply vented to the atmosphere. These gases contain both gaseous and particulate-phase pollutants arising from the combustion process and the interaction between the gases and the hot lubricating oil. In 2007 the U.S. Environmental Protection Agency (EPA) promulgated regulations for medium and heavy duty diesel engines for 0.01 g/hp-hr of particulate emissions. These regulations specified that particulate mass contained in the blowby gases had to be included with the exhaust particulate mass emissions from the engine in terms of certification to the 0.01 g/hp-hr standard. This regulatory change led to essentially universal adoption of closed crankcase ventilation (CCV) systems. With a CCV system, oil mist and other particulates are removed with an oil separator, and crankcase gases are routed back into the air intake system. Inclusion of an oil separator is important to prevent degradation of downstream intake

components resulting from their exposure to excessive amounts of lubricating oil aerosols. However, as several recent works have shown, the residual oil mist in the air intake can still deposit on components such as intercoolers [1] or turbocharger compressors [2, 3, 4, 5], leading to compressor efficiency degradation.

A number of researchers have characterized crankcase emissions in the past. Hare and Baines [6] examined sizes of particulates from diesel crankcase emissions and also extensively characterized their elemental and molecular compositions. Clark et al. [7] measured PM mass and sizes of a 1996 tractor truck and compared them with tailpipe emissions. Further studies were performed by Tatli and Clark [8] on 4 different diesel engines at different operating conditions, where they found that size distributions and number concentrations varied substantially from engine to engine. Finally, Johnson et al. [9] reported number size distributions of crankcase emissions from a fired and motored compression ignition engine at different oil temperatures, engine speeds and loads and also compared variations in the size distributions as a function of different operating conditions.

This study attempts a more comprehensive understanding of the oil aerosols emitted from the crankcase by characterizing not only their particle size distributions, but also their morphology and chemical composition, specifically investigating potential differences between the bulk oil chemistry and the composition of the oil mist. These potential differences are important in the context of developing improved components in the intake system to reduce the impact of oil aerosols on the performance and reliability of future engines. Evaluations are conducted at different engine load/speed combinations, two different lubricating oil formulations, and three different oil separator technologies.

ENGINE CELL EXPERIMENTAL SETUP

Blowby Sampling Methodology

The work was performed on a medium-duty diesel engine in a dynamometer cell. As shown in [Figure 1](#), a 1.52-m (5-ft) long, 98-mm (4-inch) diameter dilution tunnel was suspended horizontally above the engine and sampled from either the valve cover or the oil separator with electrically-conductive tubing. The dilution tunnel was used in order to avoid condensation and to control particle concentrations to within the allowable measurement ranges for the particle-sizing instrumentation. Dilution air was drawn in from the ambient through a HEPA filter; a variable speed roots blower regulated the total flow through the tunnel. The volumetric CCV flow into the dilution tunnel varied, and dilution ratios were kept constant by varying the speed of the roots blower. Sample probes of different diameters were used to facilitate isokinetic particle sampling at different total dilution tunnel flows. 47 mm filter holders were attached using separate probes to collect particles for chemical analysis, and to sample with an electrostatic precipitator to collect particles for microscopy analysis.

The dilution ratio was measured by comparing the CO₂ concentration in the dilution tunnel with the exhaust CO₂ concentration. It was assumed that blowby CO₂ and exhaust CO₂ were the same. Total gas volume flowing through the filters was measured by dry gas meters attached downstream of the filters.



Figure 1. Photograph of aerosol sampling apparatus installed in an engine cell.

Oils, Separators, and Load Points

[Table 1](#) lists the engine oils, oil separators, and engine speed and load points used in this work. A total of 22 conditions were tested using different combinations of the engine oils, separators, and engine speed and load points. Not all different separator-engine speed/load points were tested with the 3 engine oils. For particle size characterization, each test condition was sampled three times to ensure reproducibility. In addition, two of the test conditions were sampled at two non-consecutive times with the particle size measurements and XRF. Separator M was a cyclonic-type separator, Separator C was a type of variable impactor, while Separator P contained a coalescing filter.

Separator M was a 6-chamber cyclonic separator with a bypass orifice to manage pressure deltas. It had a low speed entrance area and an oil sump with a checked drain. Separator C was a variable impactor system that opened more flow passages at higher flow rates and utilized media such as fleece on the impactor wall. This particular sample used a separate drain nozzle to allow a continuous drain opportunity. Separator P contained a fine coalescing filter with a significant pressure drop and utilized boosted air from the engine to create the pressure delta required to drive the system.

Table 1. Engine conditions, engine oils, and oil separators used in this study.

Engine oils	Oil Separator	Load points
Used Oil A	None	600 rpm, 40% load
New Oil A	Separator M	2800 rpm, full load
New Oil B	Separator C	1600 rpm, 80% load
	Separator P	2300 rpm, full load

Three different oils were tested. Oil A was sampled in “Used” and “New” conditions, where the “Used” version had undergone ~ 100h of dynamometer testing, and “New” is fresh oil that had been run in the engine for 5 hours prior to sampling. [Table 2](#) enumerates other properties of these oils. Aside from viscometrics, the other major difference between Oils A and B is that Oil B has a synthetic base stock component whereas Oil A is primarily mineral-based. All testing with a particular oil with different separators and speed/load points was completed on the same oil fill. After test completion with one oil, the oil was drained, the oil filter changed. New oil was then flushed through the engine once and drained. Finally, the oil filter changed again and the oil re-filled before testing proceeded with the subsequent test oil.

Table 2. Lubricating oil properties.

	Used Oil A	New Oil A	New Oil B
Condition	~100 hours dyno testing	5 hours conditioning	5 hours conditioning
TGA soot%	1.3	0.2	0.2
Kinematic viscosity at 40°C, cSt	83.29	78.28	92.80
Kinematic viscosity at 100°C, cSt	12.68	11.90	14.88
Basestock	Mineral-based		Groups 3 and 4
Additive package	Oil A and Oil B additive packages differ		



Documents

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PARTICLE CHARACTERIZATION

Particle Size

Two different instruments were used to collect particle size data. A model 3936 Scanning Mobility Particle Sizer (SMPS) from TSI, Inc. measured electrical mobility diameters for particles smaller than a micron. A model 3321 Aerodynamic Particle Sizer (APS) from TSI, Inc. measured aerodynamic diameters for particles with diameters from 0.5 micron to 10 microns. A model 3302A Aerosol Diluter from TSI was used to further dilute the sample flow to the APS with a 100:1 dilution ratio. Mass distributions were calculated by the instrument software using a particle density of 0.85 g/cm³ and assuming spherical particles composed primarily of oil.

Particle Morphology

Particles were collected for transmission electron microscopy (TEM) analysis using an electrostatic precipitator developed by Fierz et al. [10]. Electrostatic precipitation involves migration and deposition by particle electrical mobility. It avoids deposition by impaction [10, 11, 12, 13], a mechanism sometimes associated with alteration of morphology. In the sampler, particles acquired a positive charge in a unipolar diffusion charger and migrated by way of their electrical mobility to the sample substrate (grid) held at negative potential. The device has high nanoparticle collection efficiency and uniform particle collection across the sample substrate; so a small area can be analyzed and the results can be extrapolated to the entire surface of the grid [10]. The number of charged particles is measured by an electrometer and the sampling time is computed and output by the instrument to prevent under or over sampling. The collection efficiency has been measured as a function of particle size for particles 20 to 320 nm. As shown by Fierz et al. [10], collection efficiency decreases with increasing particle diameter. This is because the electrical mobility of particles decreases as particle size increases. The sampling efficiency was adequate for the size range of particles emitted pre- and post-separator. Particles were collected on 300-mesh copper grids with carbon film (Electron Microscopy Sciences, PA). Samples were analyzed at 0.71×10^5 and 1.35×10^5 magnification and at 200 keV using a Tecnai 20 TEM (FEI Co., Netherlands) in the Shared Research Equipment (SHaRE) User Facility of Oak Ridge National Laboratory.

Chemistry

X-Ray Fluorescence

X-ray Fluorescence (XRF) was used to quantify elements with atomic number 11 (sodium) and higher. Under the conditions used for these samples, lighter elements could not be detected. To determine the composition of the oil mist, 6 - 23 mg of oil mist was collected on 47 mm diameter Teflo filters with a 2 µm pore size. The mass of the oil mist collected on the filters was determined by the difference in the weight of each filter before and after deposition. Each oil mist filter

sample was supported on a 6.3 µm polypropylene film and analyzed in a helium atmosphere to prevent volatilization during XRF analysis. Samples were analyzed on the day of collection. The concentrations of detected elements (in wt%) reported here are based on the mass of the material collected on each filter, and results are considered semi-quantitative. For mass balance, the sum of the unmeasured light elements (i.e. H, C, N, O) was determined by difference (about 99% of the sample). Bulk oils were also analyzed using XRF with a helium atmosphere by placing 5 mg samples in 38 mm diameter liquid cells with 6.3 µm polypropylene support films.

Prior to the work, three different types of filters were tested to see if they contained elements in common with those present in engine oil. Two of the filters were found to contain high background levels of oil additive elements whereas the Teflo filters did not.

XRF intensity data were collected using a PANalytical PW2400 sequential WDS XRF spectrometer fitted with a chromium X-ray tube. Quantitative analysis calculations were conducted using UniQuant5, a fundamental parameter XRF analysis program. Sensitivity factors for Ca, Cl, Mg, P, S and Zn were calculated using NIST SRM1848 Lubrication Oil Additive Package.

Thermal Desorption Gas Chromatography and Mass Spectrometry

For analysis of the engine oil base stock and non-metal-containing oil additives (i.e. organic compounds), thermal desorption-pyrolysis gas chromatography -mass spectrometry (GC-MS) was utilized. The pyrolysis unit was from Frontier Laboratories, and interfaced to the sample inlet of the GC-MS (Agilent 5975 MSD.) The samples were collected on pre-fired 47mm quartz fiber filters (Sunset Laboratories, Inc.) For each filter that was collected, a 0.5 x 1 cm section was cut out and analyzed in two steps. The first step was a thermal desorption step from 150°C to 350°C in helium. The second step was pyrolytic desorption at 400°C in helium. For both steps, the GC temperature ramp was from 40 - 320°C, and a DB-5 column was used for separation. The MS was scanned at 1 Hz between 40 - 600 Da in electron impact ionization mode (EI).

RESULTS

As mentioned in the preceding section, 22 different combinations of engine speed/load conditions, engine oil, and separator conditions were tested. This section provides a snapshot of some of the main observations from these tests. For brevity, only the engine speed may be specified in the text and figures but this is to be understood as having the load condition specified in [Table 1](#).

Particle Size Distributions

[Figures 2](#) and [3](#) show particle size distributions for New Oils A and B at 600 rpm and 2800 rpm in the absence of a separator, where [Fig. 2](#) shows the number densities and [Fig. 3](#) the mass densities.

The diameters shown are all mobility diameters; aerodynamic diameters measured by the APS have been converted to mobility diameters as described in the [Appendix](#). At 600 rpm, the number particle size distribution is lognormal with a maximum at ~ 130 nm for both oils A and B. At 2800 rpm, the number particle size distribution for both oils peaks at ~ 300 nm; however, for New Oil A, it appears to be bimodal with the small hump at 130 nm. At both speeds, New Oil B produces more particles, and at 2800 rpm, it generates a larger quantity of smaller particles than New Oil A.

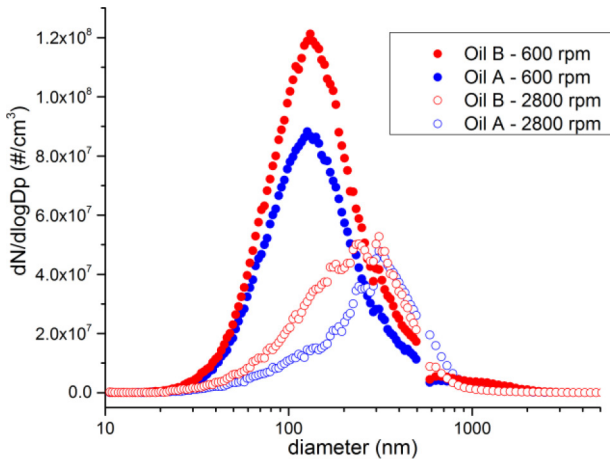


Figure 2. Particle number densities for New Oil A and New Oil B.

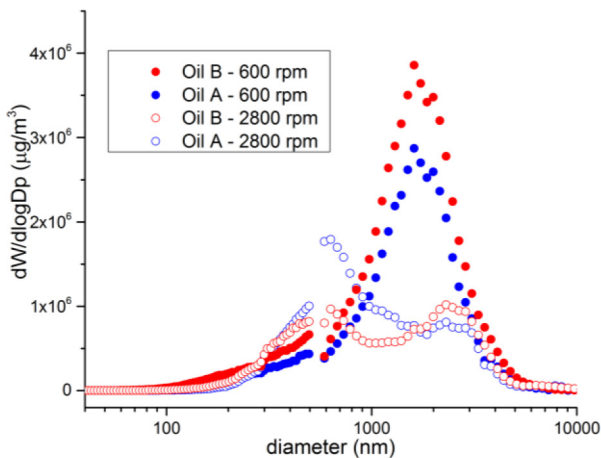


Figure 3. Particle mass densities for New Oil A and New Oil B.

When mass distributions are plotted ([Fig. 3](#)), the maxima of the curves shift to larger particles, since it is the largest particles that contribute the most to mass. The distributions at 600 rpm show a slight asymmetry with a peak at ~ 1.5 μm , with a longer tail leaning toward smaller particle sizes. The distributions at 2800 rpm are clearly bimodal for both oils with peaks at 600 nm and 2-3 μm . At 600 rpm, more particles are produced by New Oil B.

[Figures 4 and 5](#) show number and mass distributions, respectively, of Oil A under new and used conditions. At both speeds, number particle sizes did not greatly vary when oil is new or used. Used

Oil A shows a slight higher generation of smaller particles than New Oil A, as shown in [Fig. 4](#). Used Oil A also shows a bimodal mass distribution at 2800 rpm. At 600 rpm, Used Oil A appears to produce more and slightly smaller particles than New Oil A. However, all these differences are small and may also be due to measurement variability.

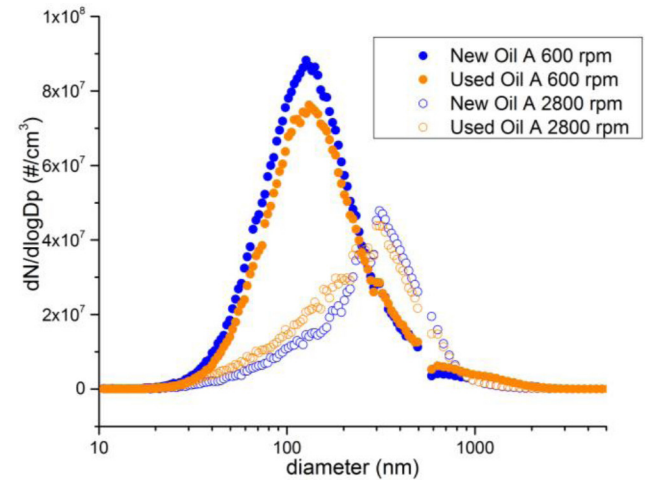


Figure 4. Particle number densities for Oil A under new and used oil conditions.

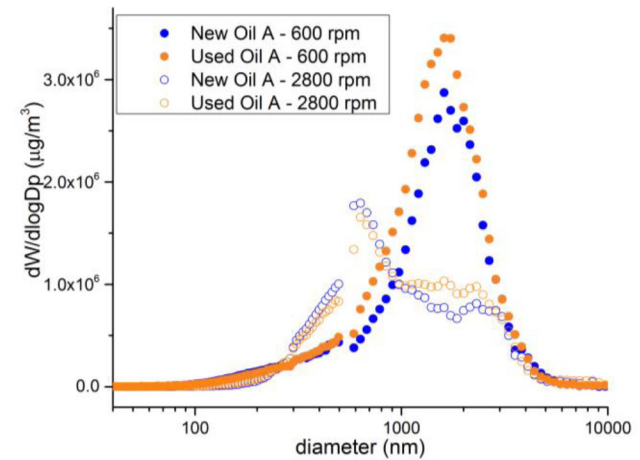


Figure 5. Particle mass densities for oil A under new and used oil conditions.

[Figures 6 and 7](#) show number densities at 600 rpm and 2800 rpm, respectively, for New Oil A with and without a separator present. At 600 rpm, Separators M and C behave similarly and their number size distributions follow the pre-separator condition, peaking at ~ 130 nm. Separator P still shows a log-normal distribution but the peak maximum is slightly shifted to a higher particle size, 170 nm. In terms of performance, Separator P is considerably more efficient than Separators M and C.

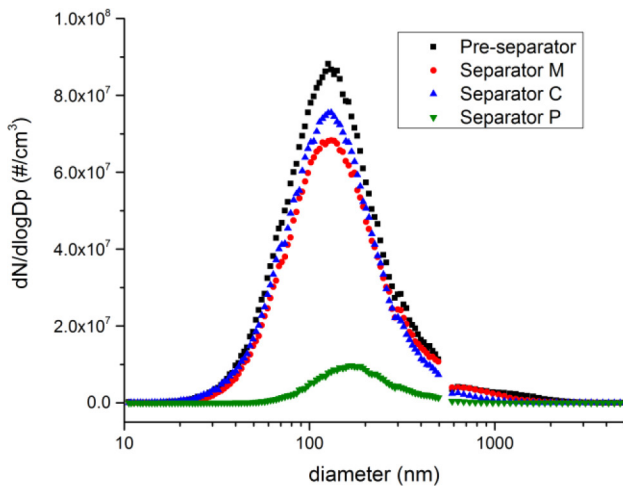


Figure 6. Particle number distributions for New Oil A using three separator technologies at 600 rpm.

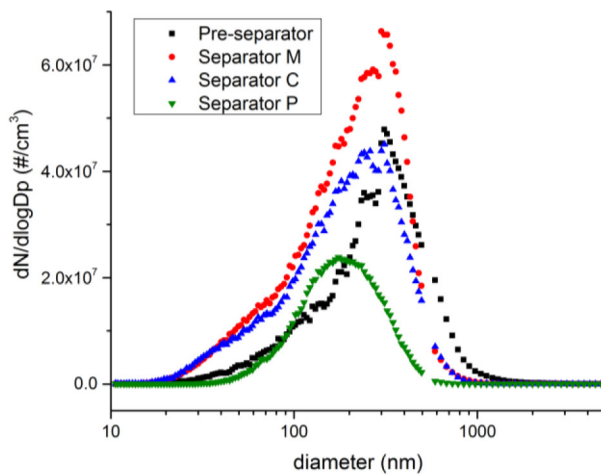


Figure 7. Particle number distributions for New Oil A using three separator technologies at 2800 rpm.

At 2800 rpm, while both Separators M and C reduce the number of particles at the larger diameters, most interestingly, they generate more particles below ~ 300 nm compared to the pre-separator condition. Separator P does not show the same generation of nanoparticles. Similar to its behavior at 600 rpm, the peak of the distribution does not follow the pre-separator condition. Separator P peaks at 180 nm whereas those of separator M and C peak at higher particle sizes, 308 nm for Separator M, 275 nm for Separator C. The pre-separator condition is at 312 nm. This result for Separator P is typical for coalescing filters, where the filtration effectiveness reaches a minimum between 100 and 300 nm. Similar to Separators M and P, there was removal of the larger particles at both speeds.

Figures 8 and 9 show the corresponding mass densities for the separator comparisons at 600 rpm and 2800 rpm, respectively. As mentioned in the preceding paragraph, the largest particles are

removed by all 3 separators. Since the largest sizes have the greatest contributions to mass, a large reduction in post-separator particles vs. pre-separator particles is observed at the larger diameters. At 2800 rpm, Separator M shows the generation of smaller particles compared to the pre-separator condition, and both Separator M and C produce a tri-modal distribution with one peak below 500 nm, a second peak at 2.8 μm , and the third at 6.5 μm . The pre-separator condition is at least bimodal, and possibly trimodal, with maxima at 582 nm, ~ 2.1 μm , and a shoulder at ~ 1.1 μm . Figs. 8 and 9 also clearly show that Separator P has superior performance with the highest mass removal at all particle sizes.

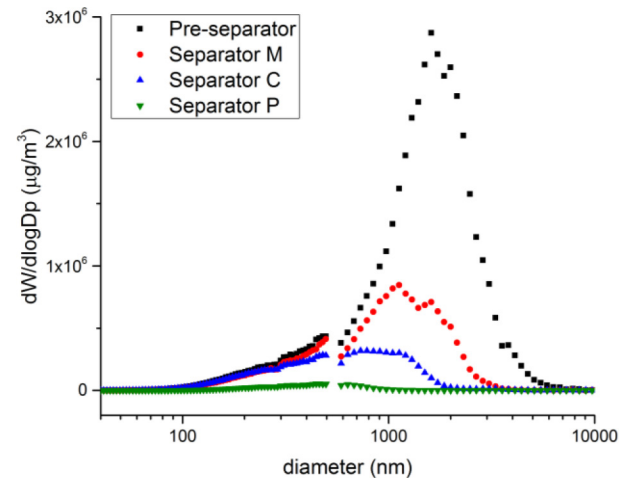


Figure 8. Particle mass distributions for New Oil A using three separator technologies at 600 rpm.

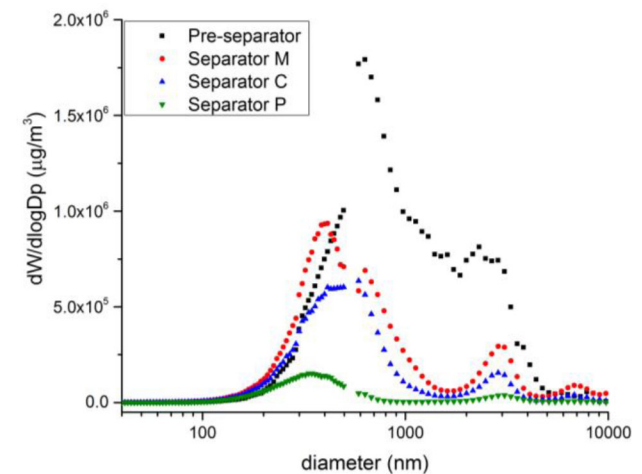


Figure 9. Particle mass distributions for New Oil A using three separator technologies at 2800 rpm.

Figures 10 and 11 show number and mass densities, respectively, for New Oil B under 4 different speed and load conditions in the absence of a separator. Note the change between 600 rpm/40% load and the higher speed and load conditions. The 600 rpm condition appears to greatly enhance the formation of a higher