

Crankcase Particulate Emissions from Diesel Engines

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ABSTRACT

In 2007, US EPA implemented the rule that the crankcase emissions be added to the tailpipe emissions to determine the total emissions from a diesel engine if the crankcase were not closed, but few data exist to quantify crankcase emissions from earlier model diesel engines. This paper presents the results of a study on the measurement of the size distribution and number concentration of particulate matter (PM) emitted from the crankcase vents from four different diesel engines under different engine speeds and loads. The engines used in the study were a 1992 Detroit Diesel Series 60, a 1996 Caterpillar 3406E, a 1997 Cummins B5.9 and a 1995 Mack E7-400. The Detroit Diesel engine was tested on an engine dynamometer and crankcase and tailpipe particulates were observed at varying engine speeds and loads. The other three engines were mounted in vehicles, and crankcase PM was observed at several engine speeds with no external load. Overall, the study showed that the size distribution and number concentration profiles of crankcase particulate emissions differed substantially from engine to engine. All three trucks examined showed a similar reduction in crankcase emissions as the engine warmed following a cold start, but an idling engine on a dynamometer differed in behavior. Also, for elevated idle speeds with a warm engine, strongly bimodal distributions were seen for all three trucks.

INTRODUCTION

Until recently, efforts to reduce particulate matter (PM) from diesel engines were focused on the tailpipe emissions. However, from 2007 U.S. on-road diesel engine PM emissions have been substantially reduced through use of exhaust filtration, to comply with the 0.01 g/bhp-hr standard. With the 2007 EPA regulations, diesel engine crankcase emissions must either be recycled to the intake or be added to the tailpipe emissions to determine the total engine-out PM emissions. This has led to the increase in interest in the characterization of particulates from the crankcase ventilation of existing vehicles in the fleet. Recently,

there has been interest in the PM loading inside school buses (Ireson et al. (2003), Sabin et al. (2004), Marshall and Behrentz (2005)), and the contribution of crankcase emissions to this loading has been quantified by Hill et al. (2005). This study has concluded that crankcase emissions were strong sources of PM_{2.5} (particles of diameter 2.5 microns or less) inside the bus.

There are not many studies of size distributions and number concentrations of particulate emissions from crankcase vents. Hare et al. (1977) published their results on the characterization of diesel crankcase emissions from a Cummins NTC-350 (turbocharged 4-stroke) and a Detroit Diesel-Allison 6V-71 (supercharger-scavenged 2-stroke). They concluded that although crankcase PM composition looked very similar to lubricating oil composition, there were enough differences such as boiling ranges and calcium content to indicate that crankcase particulates were not simply oil droplets. They also found that total particulate emissions from the crankcase were between 0.9% and 2.9% of the tailpipe emissions. Their particulate sizing tests indicated that crankcase particles were larger than the exhaust particles. Papers by Koch et al. (2002), Crane et al. (1994) and Ebner and Jasche (1998) focused on different aspects of crankcase ventilation, such as flow rate measurement methods. Some preliminary data for this paper were presented in a poster by Tatli and Clark (2005), and data from another study on crankcase characterization and abatement was published by Clark et al. (2006).

This paper presents the results of crankcase particulate number concentrations by size from a 1992 Detroit Diesel Series 60 engine on an engine dynamometer, as well as a 1996 Peterbilt tractor truck with a 1996 Caterpillar 3406E engine, a 1998 Dodge Ram 2500 truck with a 1997 Cummins B5.9 engine and a 1995 Mack tractor truck with a 1995 Mack E7-400 engine under idle conditions. The thrust of the paper is simply to make additional data available for use in inventory assessments and modeling studies.

Many factors will influence the nature, mass production and size distribution of crankcase PM. Aside from

engine design parameters, wear of the piston rings and valve guides will alter the crankcase PM as the engine accumulates operating time, and the oil viscosity (based on specification and age) is likely to affect splash and entrainment of droplets. It is also important to observe that the real-world dilution of the crankcase vent stream outside of the tube will affect the size distribution, since particles can nucleate, evaporate and agglomerate during the dilution process. Effect of dilution of exhaust gases has been shown by many workers to depend on the temperature and humidity of the diluting gas (atmospheric air in real plumes), and the dilution rate history. Crankcase gases may be affected in a similar way. Therefore the measurement reported below, of raw crankcase gases from four engines at diverse operating temperatures, cannot be considered to represent the whole fleet.

EXPERIMENTAL SETUP

The primary instrument used for the particle sizing was a DMS500 by Cambustion (Reavell et al. (2002a,b), Collings et al. (2003)). There are many particle sizing instruments, the most widely used being the SMPS by TSI (Wang and Flagan (1990), Rubino et al. (2005)). The DMS500 differs from the the SMPS in its capability of measuring multiple size bins with a time response of 200ms, whereas the SMPS can measure a single size bin for transient tests or can measure multiple bins for steady state tests with a response time of around 100 seconds for a scan. The DMS500 uses corona discharging to establish appropriate charge on the particles and then classifies them according to electrical mobility in real time. The measurement size range of the DMS500 used in this study was approximately 5nm to 1000nm.

Crankcase sampling on the 1992 DDC Series 60 engine was conducted while the engine was operated on a General Electric DC dynamometer in West Virginia University's Engine and Emissions Research Center. The engine tailpipe exhaust was directed to a full flow dilution tunnel which was 18 inches in diameter and incorporated a mixing orifice to promote mixing of the engine exhaust with the temperature conditioned test cell air. The crankcase emissions were directed outside of test cell through a 1 inch pipe. During exhaust particulate analysis, the DMS500 was connected to a secondary dilution tunnel with no added dilution. In this way the exhaust experienced a minimum dilution ratio at engine full power output. The secondary dilution tunnel was installed for instances when additional dilution (on top of primary dilution) was required to reduce sample temperatures and/or concentrations. During the measurement of crankcase particulate concentrations, the instrument sampled a portion of the

crankcase gases with its probe connected approximately 6 ft. downstream of the draft tube from the engine, as shown in Figure 1.

For the 1996 Peterbilt, the 1998 Dodge Ram 2500 and the 1995 Mack, the vehicles were tested stationary with only auxiliary loads and the particulate number concentrations and temperatures were measured at the outlet of the draft tube (crankcase vent). The average flow rates were measured using 200 and 1000 scfh Dwyer DR Series glass flowmeters (rotameters). Crankcase gases were admitted to these rotameters through a HEPA filter to prevent fouling the rotameter.

The engines were initially tested immediately following a cold start, and for the remaining tests, the engines were operated at high speed until the engine was warm. The tailpipe particulate emissions for the trucks were not tested, and the data presented are for crankcase particulate emissions. All engines in this study were tested with the existing Shell Rotella 15W40 oil in the crankcase.

RESULTS

1992 DETROIT DIESEL SERIES 60 ENGINE

The engine specifications used in this study are given in Table 1 (Tables are given at the end). For this engine, both diluted tailpipe exhaust and raw crankcase particulate concentrations were measured. Figure 1 shows photographs of the engine in the test cell and of the sampling probe.



Figure 1: 1992 DDC Series 60 engine and the sampling port (The crankcase was vented through the 1 inch nominal diameter pipe and the sample was collected through the T junction.)

Table 2 shows the tests conducted for both the diluted tailpipe exhaust and crankcase particulate emissions, and also gives the average oil temperature and the flow rate from the draft tube. See the Appendix for more information on crankcase flow rates. In Table 2, FTP represents the US EPA Federal Test Procedure heavy-duty transient cycle used for emission testing of heavy-duty engines, defined in *CFR Title 40 Part 86*.

Figure 2 shows the particulate size distribution profiles from the crankcase during engine idling at 600rpm for four different instances, namely 5 seconds after start, 5 minutes after start, 20 minutes after start and during hot idle. The engine was considered hot when oil temperature remained constant for more than 3 minutes. The size distribution profile shifted towards larger sized particles as the engine became warmer. Initially, a single mode with a peak around 75nm was observed, while with increasing temperatures, broad or bimodal distributions with peaks at around 100nm and 175nm were seen.

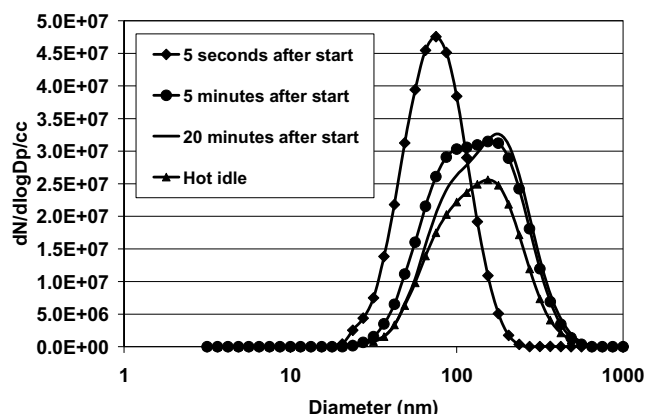


Figure 2: Size distributions of crankcase particulate emissions under idling conditions at different temperatures for the DDC Series 60

The size distributions from both the diluted tailpipe exhaust and crankcase were measured during the FTP transient cycle. The estimated dilution ratio (calculated as total dilution tunnel flow divided by engine exhaust flow) of the tailpipe exhaust varied between approximately 2.5 and 23 (Figure 3), with the assumption that the engine exhaust mass flow rate was equal to the intake air flow rate for this calculation. The nature of dilution will affect the subsequent particle size distribution, particularly with respect to nanoparticle formation, and so the data will not necessarily represent the situation found in an exhaust plume in real world operation.

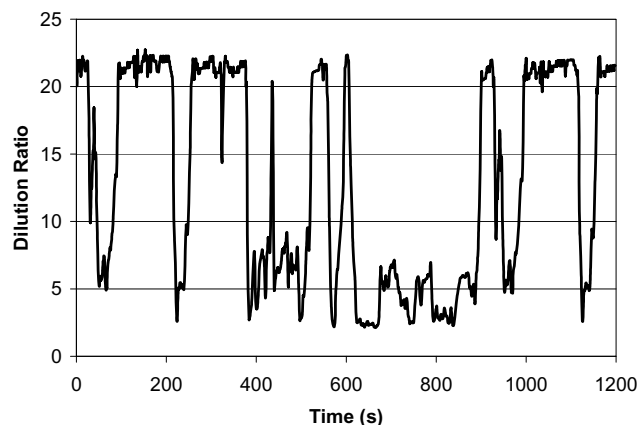


Figure 3: Dilution ratio during the tailpipe emissions testing using the primary dilution tunnel with the 1992 DDC engine during the FTP transient cycle

Figure 4 shows the engine speed profile during the FTP transient cycle.

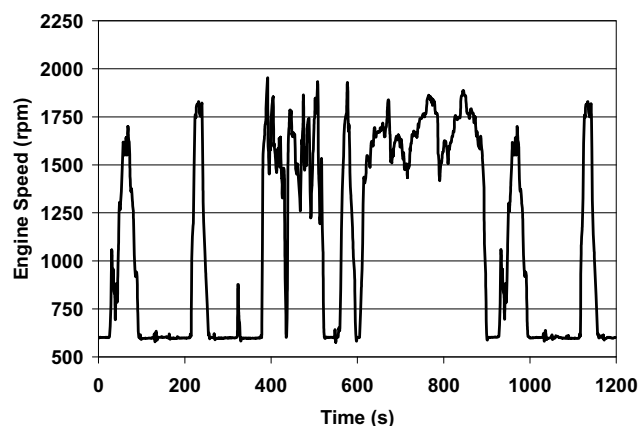


Figure 4: Engine speed profile during the FTP transient cycle

Figure 5 gives the contour plots of size distributions of particulate emissions from both the diluted tailpipe exhaust and the crankcase throughout the cycle. The particulate emissions from the crankcase were mainly single mode with maximum number concentration occurring near 150nm. The concentrations increased and spread to smaller sizes during acceleration periods, conserving a single peak structure. For the tailpipe particulate emissions, the majority of the particles (by number) were in the nucleation mode, forming a single mode at around 20nm, and a bimodal distribution with accumulation mode particles in the 150nm range formed during the acceleration periods.

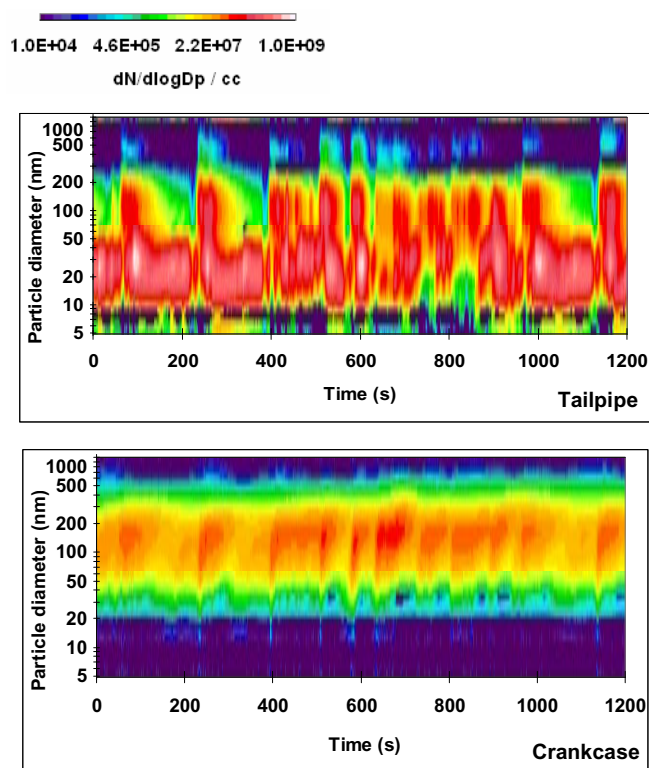


Figure 5: Contour plots of particulate size distributions for both the tailpipe and the crankcase for the 1992 DDC engine (tailpipe concentrations corrected for dilution ratio)

Figure 6 gives cross sectional size distribution profiles from Figure 5, during acceleration ($t = 1150$ sec) and deceleration ($t = 1000$ sec). In these distributions, the particle number concentrations from the tailpipe are on average an order of magnitude greater than number concentrations from the crankcase vent.

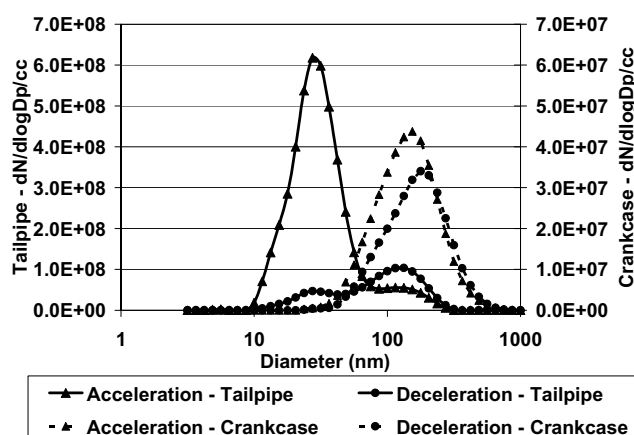


Figure 6: Size distribution profiles for both the crankcase and the tailpipe for the 1992 DDC engine (tailpipe concentrations corrected for dilution ratio) during acceleration and deceleration

The final characterization effort for the 1992 DDC Series 60 engine was to measure the crankcase

particulate emissions during steady state loaded tests. The engine was tested with two different loads and three engine speeds. Figure 7 shows the average profiles during each engine speed and load interval.

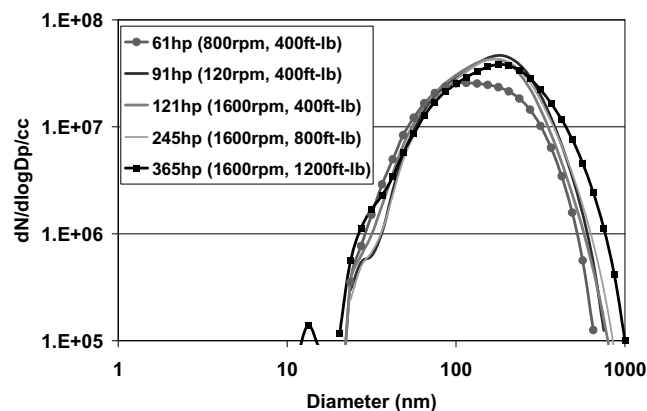


Figure 7: Size distribution profiles of crankcase particles during the steady state tests for the DDC Series 60 engine

Figure 7 shows that the size distributions did not change substantially for the five different steady state conditions. During operation at an engine speed of 1600 rpm and torque of 1200 ft-lb, artifacts around 15nm were observed.

1996 PETERBILT TRACTOR TRUCK (WITH A 1996 CATERPILLAR 3406E ENGINE)

The vehicle and engine specifications are given in Table 1. The vehicle was stationary and was operated at several speeds with only necessary auxiliary loads. Speeds were 700rpm (idle), 1000rpm, 1500rpm and 2000rpm for the crankcase particulate measurements. Figure 8 shows photographs of the vehicle and the sampling probe, which was situated as the draft tube outlet. The ambient conditions during the testing of the vehicle are given in Table 2.



Figure 8: 1996 Peterbilt tractor truck and the sampling port

Table 2 also gives the tests that were run for the crankcase particulate sampling, the average temperatures right at the outlet of the draft tube and the average flow rates. Figure 9 shows the size distribution