

The Effect of Cetane Improvers and Biodiesel on Diesel Particulate Matter Size

2011-01-0330

Published
04/12/2011John Nuszowski, Kevin Flaim and Gregory Thompson
West Virginia Univ.

Copyright © 2011 SAE International

doi:10.4271/2011-01-0330

ABSTRACT

Heavy-duty diesel engines (HDDE), because of their widespread use and reputation of expelling excessive soot, have frequently been held responsible for excessive amounts of overall environmental particulate matter (PM). PM is a considerable contributor to air pollution, and a subject of primary concern to health and regulatory agencies worldwide. The U.S. Environmental Protection Agency (EPA) has provided PM emissions regulations and standards of measurement techniques since the 1980's. PM standards set forth by the EPA for HDDEs are based only on total mass, instead of size and/or concentration. The European Union adopted a particle number emission limit, and it may influence the U.S. EPA to adopt particle number or size limits in the future.

The purpose of this research was to study the effects biodiesel blended fuel and cetane improvers have on particle size and number. In addition, a special interest was taken into the variations in diesel particulate matter (DPM) measurements due to the fuel alteration. The Cambustion DMS-500, a fast particle spectrometer, was used to continuously sample diesel aerosol from a HDDE test-cell dilution tunnel with the engine exercised over transient and steady state test cycles. Samples were taken from the primary dilution tunnel and were further diluted in a secondary dilution system. A rebuilt 1992 Detroit Diesel DDC S60 was tested using petroleum-based diesel fuel, biodiesel blended fuel, and a cetane improving additive (2-EHN).

The use of cetane improving additives generally resulted in concentration reductions for all of the measured particle sizes that were affected. The blending of biodiesels with petroleum-based fuels has been known to reduce PM mass-based emissions; and in this research it reduced the particle concentrations in the 6 nm to 56 nm and 100 nm to 487 nm size range and did not affect those of the other sizes during transient testing.

INTRODUCTION

After decades of emissions regulations, tailpipe pollution from fossil fuel combustion is still threatening the environment and human health in the United States of America. The Environmental Protection Agency (EPA) claims that at least half of all Americans reside in areas that do not meet the basic standards of air quality. In major cities, vehicles are responsible for at least 50 % of the total pollution and an even larger portion of the air pollution. Around 80 % of the air-related cancer risk in some cities can be attributed to tailpipe emissions [1].

Particulate matter (PM) from heavy-duty diesel engines (HDDE) is one of several emissions that are considered harmful by the EPA. The wide variety of organic compounds, temperatures, and pressures that a diesel combustion mixture undergoes causes diesel engines, by nature, to emit greater amounts of particulates (on a mass per energy basis) than gasoline engines [2]. EPA regulations and the general need for greater combustion efficiency have forced diesel engine manufacturers to decrease total PM emission levels drastically. Since 1988, HDDE PM emissions standards have decreased from 0.6 g/bhp-hr (1988) to the present 2010 standard of 0.01 g/bhp-hr. The U.S. regulations currently do not consider particle size, but the European Union (Euro 5/6) legislation introduced a particle number emission limit (PMP method). Little is known about the direct effects of diesel

particulate matter (DPM) on human health, but studies suggest that particles smaller than 50 nm have adverse effects if inhaled [3, 4, 5]. It is noted that since 2010, on-road HDEs have incorporated some form of particulate trap to reach the 0.01 g/bhp-hr PM regulation limit but off-road and legacy engines are not obligated to incorporate this PM reduction technology.

PM is generally divided into four categories based on equivalent aerodynamic diameter. PM₁₀ includes all particulates of aerodynamic diameter less than 10 µm. The D₅₀ cut size is considered to be 10 µm, meaning that 50 % of the respirable particles are smaller than 10 µm. Fine particles are of aerodynamic diameter less than 2.5 µm [2]. Ultrafine particles are of diameters less than 100 nm, and nanoparticles are characterized by diameters less than 50 nm. There are also modal size classifications that are used to describe typical PM mass and number distributions. Coarse mode includes any particle with a diameter greater than 1 µm. Coarse mode typically contains 5 % to 20 % of the total mass, but less than 1 % of the total particle count. Extending through fine, ultrafine, and part of the nanometer range, accumulation mode contains sub-micron particles ranging from 40 nm to 1000 nm. Nuclei mode includes particles between 7 nm and 40 nm.

Due to physical changes that diesel particulates continuously undergo, DPM is not a well-defined chemical species [3]. In the existing literature, there is much uncertainty concerning the measurement results of DPM [6, 7, 8, 9, 10]. For the underlying study, DPM is the non-gaseous component emitted from raw diesel exhaust that has been diluted and cooled. Previous research has investigated the particle number and size distribution under transient testing [11,12], albeit without looking at the repeatability aspect of transient testing.

Biodiesel blended fuel generally decreases CO, PM, and HC, while showing variable NOx emissions [13, 14, 15, 16, 17]. The oxygen content in the biodiesel enhances oxidation in the premixed-flame and post premix flame [18]. Cheng and colleagues [18] used numerical modeling to show that as the oxygen content increases, oxidation of carbon to CO and CO₂ increased in the premixed flame region, which reduces the carbon available for soot precursors. In addition, the increased oxygen content increases radical content in the post premix flame region, which oxidize aromatics and limit the growth of polyaromatic hydrocarbons. Most studies on biodiesel blended fuel emissions are performed on a mass basis. Meaning, the reduction in PM is a reduction in the PM mass emitted from the engine. Smaller particles, which have a greater number, tend to be lighter and therefore have a smaller mass. The number of smaller particles could increase while still having a reduction in PM mass due to a reduction

in the larger, heavier particles. A study by Tinsdale et al. [19] showed an increase in nucleation mode particles, even though a reduction in total particle number, accumulation mode particle number, geometric mean particle size, particulate mass, and soot mass emissions was found by blending biodiesel with petroleum diesel. In general, studies [17,19, 20, 21] show a reduction in mean diameter, total particle number, and total particle mass concentration. For a review of the emissions from biodiesel blended fuels see Lapuerta et al. [17].

The cetane number of a fuel is an indication on the ignitability of the fuel. By increasing the cetane number of the fuel, with the addition of a cetane improver additive, ignitability of the fuel is increased and the ignition delay is shorter creating an earlier start of combustion. The addition of a cetane improver to a base fuel has been shown to decrease NOx emissions [22]. Specifically, cetane improvers have garnered interest by reducing or removing the NOx penalty from using biodiesel blends [13,14,22]. Little research or no research has been done on the PM number and size distribution due to the PM mass emissions showing little or no significant difference compared to the base fuel [13,14].

This research was conducted to understand the effects on particle number and size when adding a cetane improver or biodiesel to a base petroleum diesel fuel. Specific emphasis was taken on repeating transient tests to ascertain the minimum detectable variations in particle number and size. Both steady state and transient testing was utilized with these fuels.

EXPERIMENTAL SETUP

The data from this study was taken from a full-scale critical flow venturi (CFV) dilution tunnel at the WVU Center for Alternative Fuels, Engines, and Emissions (CAFEE). The laboratory is compliant with the standards set by ISO 8178 and 40 CFR Part 86, Subpart N [23]. The test cell was designed for regulated emissions testing, and it contains four essential components. A dynamometer was used to measure and control engine speed and torque during test cycles. A CFV dilution tunnel provided an environment that allowed for controlled DPM formation and measurement. Additional details regarding the regulated emissions can be found elsewhere [22]. The emissions sampling equipment for particle concentration and sizing included a constant flow ejector diluter, a secondary NOx analyzer, and a Cambustion DMS-500 fast particle sizer. The primary laboratory apparatus is illustrated in Figure 1. The particle sizing and concentration components are within the perimeter of the dashed line and have a sampling apparatus that is unique to this work.

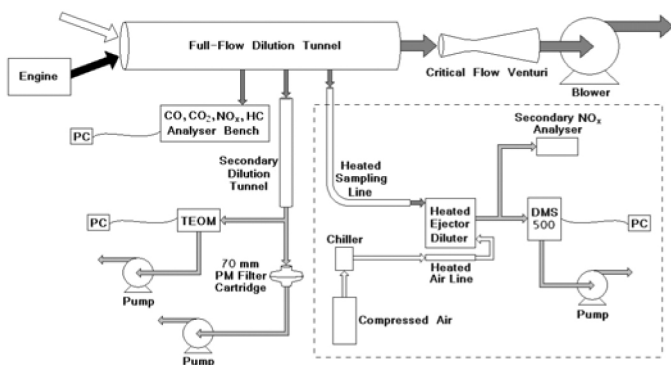


Figure 1. Components of Exhaust Sampling System

The engine tested was an on-road heavy-duty diesel engine. [Table 1](#) displays basic specifications for the engine used in this study. This engine was selected as being representative of a legacy engine that may be found on or off road that are relatively higher DPM emitters of concern.

Table 1. Test Engine Specifications

Engine Manufacturer	Detroit Diesel Corporation
Engine Model, Year	Rebuilt DDC Series 60, 1992
Configuration	Inline 6 cylinder
Displacement (L)	12.7
Power Rating (hp)	360 @ 1810 rpm
Torque Rating (ft-lb)	1450 @ 1200 rpm
Compression Ratio	15:1
Bore x Stroke (mm x mm)	135 x 165
Air Handling	Turbocharged, Aftercooled
Exhaust Gas Recirculation (EGR)	N/A

The transient HDDE Federal Test Procedure (FTP) was used in order to simulate on-road operating conditions. The Supplemental Emissions Test (SET), which is a 13-mode steady state test, was also necessary for discriminating subtle differences in test repeatability and particle size distribution due to steady state versus transient operation since most particle size and number research is done at steady state.

A Cambustion DMS-500 was chosen for this study because of its ability to detect transient particle distributions. During operation of the Cambustion DMS-500, the diluted exhaust sample was drawn through the aerosol charger. Then the

charged aerosol entered the classifier, which was surrounded by clean sheath flow. An electric field caused particles to drift toward the electrometers, or electrode rings. The charged particle trajectory and the ring on which a particle landed depended on drag and momentum (mass and charge). The denser the particle was, the farther it traveled within the DMS. The measurements of the DMS were consequently based on equivalent mobility diameter.

Initially, the aerosol sample was taken directly from the primary dilution tunnel. This caused the DMS to over range for several minutes during an FTP. Therefore, a secondary dilution system for the DMS-500 was incorporated. A heated ejector diluter was custom built to provide the DMS-500 with an aerosol sample from the main dilution tunnel at a constant secondary dilution ratio. [Figure 2](#) is a schematic of the heated ejector diluter. The ejector diluter system provided accurate and repeatable measurements. The system was designed to maintain the sample at 47 ± 1.0 °C. This was done by heating the slip stream sample from the primary dilution tunnel and maintaining enclosed components at isothermal conditions. A HEPA capsule filter ensured that a minimal amount of particles from the compressed air supply entered the system. A precision regulator incorporated a bleed off valve to maintain a constant pressure from the compressed air supply to the ejector diluter. The ejector diluter used the pressure and flow of the compressed air to create a vacuum that pulled in the aerosol sample. Once the aerosol and compressed air mixed in the ejector diluter, some of the diluted sample was sent to the DMS while the rest was evacuated to the ambient. The ejector diluter consisted of two parts; an air operated vacuum pump and a critical flow orifice. The air supply pressure was directly proportional to the resulting vacuum pressure. As long as the vacuum was greater than 16 in Hg, the critical orifice ensured a constant flow rate of sample through the diluter. The dilution ratio could be adjusted, to a certain extent, by varying the air supply pressure (which changed the flow rate of dilution air) at the precision regulator. For greater adjustment of the dilution ratio, the critical orifice could be substituted with a different size critical orifice. With adjustment to the regulator and changing of the critical orifice (orifices ranging from 2 lpm to 15 lpm), a constant dilution ratio could theoretically be set at anywhere from 7.80 to 67.5. The mass flow meter monitored the air flow and pressure into the ejector diluter for quality assurance and data acquisition purposes only.

Properly maintaining the temperatures of the aerosol sample and dilution air was crucial. An increase or decrease of 3 °C on either side of the ejector diluter could cause a change in dilution ratio of about 2 %. The ejector dilution system's ability to maintain a constant dilution ratio depended mostly

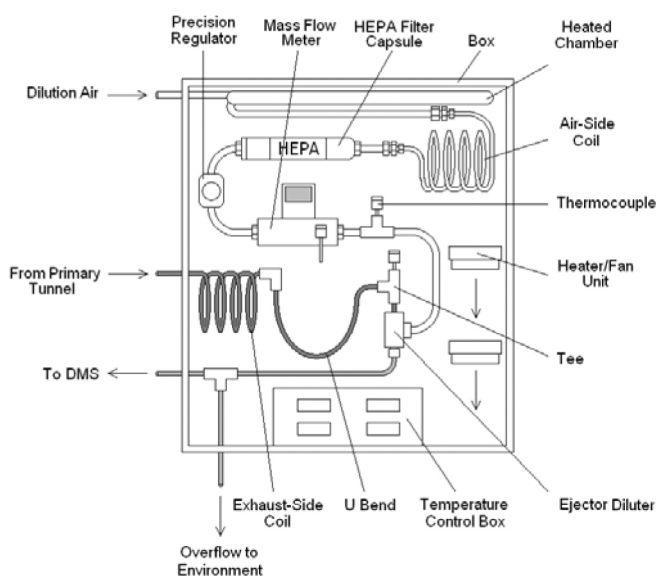


Figure 2. Secondary Dilution System Design

on: the heaters' ability to maintain constant temperature, the regulator's ability to maintain constant pressure, the orifice's ability to maintain constant sample flow, and the vacuum pump's ability to maintain sufficient vacuum pressure and constant air flow. The secondary dilution ratio was verified using two NO_x analyzers during several SETs. The combined results yield a secondary dilution ratio with an average value of 24.05, a maximum value of 25.32 (5.28 % higher), and a minimum value of 23.06 (4.12 % lower). The ability of the secondary dilution system to maintain a constant dilution ratio may actually be better than indicated, because variation in NO_x measurements is included in the calculation of the maximum and minimum values.

The procedure in which data was collected was consistent from test to test. The heated ejector diluter was given at least one hour to stabilize its internal temperature. The precision regulator pressure was set to 80 psi, which resulted in a constant secondary dilution ratio of ~24. The DMS was given at least forty five minutes to warm up and stabilize before each test session. The electrometer rings within the DMS were "zeroed" about five minutes before the start of each test to minimize drift. The orifice plates within the remote impactor on the DMS sampling line were changed in order to maintain a sample flow of 8 lpm $\pm$ 10 %. In the 20 minutes between hot start FTPs, the DMS was reset and the rings were rezeroed. Data logging on the DMS's data acquisition system began about one minute before the test started and continued one minute after each test. To align the DMS data with the test-cell data, engine speed was logged by

the DMS and compared against the DMS continuous concentration of 100 nm particle size bin and the peaks were matched. At the end of each day, the electrometer rings were cleaned with isopropyl alcohol and "chem wipes." The full-scale dilution tunnel maintained a nominal flow of approximately 2400 scfm, which resulted in main-tunnel dilution ratios of about 22 at idle and 2 at full power. Therefore, the overall dilution ratio at the intake of the DMS ranged from about 480 to 48 during each FTP.

In an attempt to understand the affects biodiesel blends have on particle size and number distributions, steady state and transient testing was performed using three fuels. The fuels consisted of one low cetane reference fuel (LC) and two biodiesel blended fuels - one at a 10% concentration (LC B10) and the other at a 20% concentration (LC B20). The LC B10 was a mixture of 90 % LC diesel and 10 % soy-derived biodiesel, by volume, and LC B20 was 80 % low cetane and 20 % soy derived biodiesel, by volume. To obtain some level of statistical significance, three hot-start FTPs were run on each fuel. The fuel properties for the LC, LC B10, and LC B100 fuels are shown in [Table 2](#).

Additionally, the same LC reference fuel was used with 2-EHN concentrations of 0.08%, 0.16%, and 0.21%, by volume, to find emissions advantages using this additive. The tests consisted of 12 hot-start FTPs runs on the rebuilt 1992 Detroit Diesel DDC S60 engine. The fuel properties for the LC reference fuel are shown in [Table 2](#) as "LC 0% 2-EHN." The testing on the biodiesel blends was conducted months after the 2-EHN tests and therefore, an addition fuel sample was taken and analyzed on the LC reference fuel. For the LC reference fuel with 2-EHN concentrations of 0.08%, 0.16%, and 0.21%, by volume, cetane numbers of 46.7, 49.0, 49.9, respectively, were obtained.

BIODIESEL RESULTS

The evaluation of the LC, LC B10, and LC B20 fuels consisted of three hot-start FTPs performed for each fuel on the same day to minimize day-to-day variations. The average and coefficient of variation (COV) are shown for the integrated brake-specific mass emissions in [Table 3](#). The brake-specific mass emissions were repeatable with a maximum COV of 1.5%. The maximum COV of 1.5% for total particulate matter (TPM) shows the repeatability of the mass emitted PM from the engine. Compared to the base fuel, LC B10 and LC B20 reduced TPM mass emissions by 10% and 20%, respectively.