

# Effects of Biodiesel Blends on Particulate Matter Oxidation in a Catalyzed Particulate Filter during Active Regeneration

2010-01-0557

Published  
04/12/2010Gregory Austin, Jeffrey Naber, John Johnson and Chris Hutton  
Michigan Technological Univ.

Copyright © 2010 SAE International

## ABSTRACT

Active regeneration experiments were performed on a production diesel aftertreatment system containing a diesel oxidation catalyst and catalyzed particulate filter (CPF) using blends of soy-based biodiesel. The effects of biodiesel on particulate matter oxidation rates in the filter were explored. These experiments are a continuation of the work performed by Chilumukuru et al. in SAE Technical Paper No. 2009-01-1474, which studied the active regeneration characteristics of the same aftertreatment system using ultra-low sulfur diesel fuel.

Experiments were conducted using a 10.8 L 2002 Cummins ISM heavy duty diesel engine. Particulate matter loading of the filter was performed at the rated engine speed of 2100 rpm and 20% of the full engine load of 1120 Nm. At this engine speed and load the passive oxidation rate is low. The 17 L CPF was loaded to a particulate matter level of 2.2 g/L. Active regeneration was then performed using fuel dosing in the exhaust, which was oxidized at 75-80% conversion efficiency in the diesel oxidation catalyst. Temperatures from 475°C to 550°C at the inlet of the CPF were examined. Experiments were performed using ultra-low sulfur diesel, 5 and 20% biodiesel blends in order to determine the particulate matter oxidation dependence upon biofuel percentage and to compare with the previous results with ultra-low sulfur diesel. A method was developed to produce more accurate measures of the particulate matter loading in the CPF and improve the estimation of the thermal oxidation rate during active regeneration. In addition to the particulate matter mass, measured parameters included pressure drop, filtration efficiency, particle size distribution, and gaseous emissions.

Results with 20% biodiesel show a reaction rate five times higher in the particulate filter for active regeneration as compared to ultra low sulfur diesel. For example, for a CPF inlet temperature of 525 °C, 19.6 minutes was required to oxidize 70% of the particulate matter with ultra-low sulfur diesel, as compared to 9.8 minutes with 5% biodiesel and 3.4 minutes with 20% biodiesel at the same conditions. This, combined with the lower particulate matter production from biodiesel blends, shows a significant benefit from the use of biodiesel in terms of minimizing the fuel needed to actively regenerate the particulate filter. Regenerations are not required as often, and due to the higher reactivity, more particulate matter is oxidized per gallon of dosing fuel at lower temperatures.

## INTRODUCTION

Increasingly stringent emissions regulations and the ever increasing demand for energy have fueled the demand for alternative fuels. The most common alternative fuel for diesel engines is biodiesel, which is most commonly soy methyl ester in the US. Diesel engines provide higher efficiency than gasoline engines, so they dominate the heavy-duty truck market, and an increasing number of passenger vehicles worldwide are using diesels. Diesel emissions regulations have become stricter over the years, requiring aftertreatment devices to achieve the newest required levels of emissions for both passenger and commercial vehicles. The change in United States emissions regulations for heavy-duty (HD) trucks can be seen in Table 1. As can be seen, the regulations on particulate matter (PM) emissions saw an order of magnitude drop from 2004 to 2007, driving the need for aftertreatment devices for PM reduction. Diesel particulate filters (DPFs) including catalyzed particulate filters (CPFs), which have a catalyst washcoat, are standard equipment on new on-highway diesel vehicles. Considerable research has

**Documents**

Document Sharing Hub

been performed to understand the passive and active regeneration characteristics of particulate matter in DPFs and optimize the process to minimize the fuel penalty from periodic active regeneration of the particulate filter, including the research by Chilumukuru et al. [1]. The active regeneration process is performed by the dosing of fuel as post-injection in-cylinder or directly into the exhaust stream.

**Table 1. US HD on road emissions regulations over time, all values in g/bhp-hr**

| Model Year | HC                         | CO   | NOx     | PM   |
|------------|----------------------------|------|---------|------|
| 1988       | 1.3                        | 15.5 | 10.7    | 0.6  |
| 1998       | 1.3                        | 15.5 | 4       | 0.1  |
| 2004       | NMHC + NOx – 2.5 combined* |      |         | 0.1  |
| 2007       | NMHC – 0.14                | n/a  | 0.20 ** | 0.01 |

\*-One of two options, \*\*- Phased in from 2007 to 2010

With the increasing demand for alternative fuels and biofuels, the impact of biodiesel blends on engine-out emissions has been explored in detail. This includes the study on the combustion fundamentals of NOx formation by Eckerle et al. [2]. Additionally, studies have been performed with biodiesel on the passive regeneration of PM in the DPF, with varying results. Williams et al. [3] found a 40°C reduction in the balance point temperature with 20% biodiesel (B20) and over a 100°C reduction with 100% biodiesel (B100). However, Barbier et al. [4] found little to no change with B30 fuel as compared to ultra-low sulfur diesel (ULSD). A study by Szybist et al. [5] on the characteristics of the PM produced from different biodiesel blends found a more amorphous structure for B20 PM, which is thought to be one of the reasons for the higher reaction rate of the PM. A study by Oak Ridge National Laboratory [6] on the surface oxygen content of PM found that the use of higher biodiesel percentage blends yielded more reactive PM with higher surface oxygen content. However, relatively little research has been performed on the active regeneration characteristics of biodiesel blends in DPFs, which is the focus of this study.

The specific objectives of this study are:

- To investigate the impact of 5 and 20% biodiesel blends on engine-out emissions including PM, NOx, HC, and CO while running a non-modified engine with the OEM engine control strategy.
- To determine the active regeneration characteristics of 5 and 20% biodiesel blends through fuel dosing into the exhaust stream and compare the results with previous work on the same DPF system that was conducted with ultra-low sulfur diesel fuel [1].

## EXPERIMENTAL SETUP

A 2002 Cummins ISM 246 kW (330 hp) heavy duty diesel engine with electronically controlled cooled exhaust gas

recirculation and a variable geometry turbocharger was used in this study. The engine specifications are shown in Table 2. The engine was coupled to an eddy current dynamometer (Eaton Corp., OH) rated at 373 kW (500 hp). The specifications for the aftertreatment system are shown in Table 3. The diesel oxidation catalyst (DOC) and catalyzed particulate filter (CPF) were mounted in a stainless steel “can” that could easily be removed from the exhaust line. A Cummins mid-flow doser injector with a maximum flow of 4 cc/sec at 6.9 bar was mounted on the exhaust directly after the outlet of the turbocharger to improve mixing with the exhaust. For each test, the same blend of fuel was supplied to both the engine and the doser. An axial flow exhaust gas mixer (Emitec Inc., MI) was also mounted in the exhaust just before the inlet of the DOC to increase turbulence of the exhaust and promote mixing of the dosed fuel.

**Table 2. Engine specifications**

|                             |                                      |
|-----------------------------|--------------------------------------|
| Model                       | Cummins ISM.330                      |
| Year of Manufacture         | 2002                                 |
| Cylinders                   | 6, inline                            |
| Bore & Stroke               | 125 mm x 147 mm                      |
| Displacement                | 10.8 L                               |
| Aspiration                  | Turbo Charged                        |
| Aftercooling                | Cummins Charge Air Cooler            |
| Turbocharger                | Variable Geometry Turbine (Holset)   |
| Rated speed and Power       | 2100 rpm and 246 kW                  |
| Peak Torque                 | 1697 Nm @ 1200 rpm                   |
| Common Rail pressure (peak) | 179 MPa                              |
| EGR system                  | Electronically controlled and cooled |

**Table 3. Regenerative Particulate Filter specifications**

| Specification                                                 | DOC        | CPF        |
|---------------------------------------------------------------|------------|------------|
| Substrate                                                     | Cordierite | Cordierite |
| Cell geometry                                                 | Square     | Square     |
| Diameter (mm)                                                 | 267        | 267        |
| Length (mm)                                                   | 101.6      | 304.8      |
| Total Volume (L)                                              | 4.54       | 17         |
| Cell Density (cells/cm <sup>2</sup> (cells/in <sup>2</sup> )) | 62 (400)   | 31 (200)   |
| Cell Width (mm)                                               | 1.09       | 1.49       |
| Filtration Area (m <sup>2</sup> )                             | N/A        | 15.3       |
| Frontal Area (mm <sup>2</sup> )                               | 559        | 559        |
| Channel Wall Thickness (mm)                                   | 0.175      | 0.305      |
| Wall density (kg/m <sup>3</sup> )                             | N/A        | 1130       |
| Specific heat (kJ/kg K)                                       | N/A        | 1          |
| Thermal conductivity (W/ m K)                                 | N/A        | 1          |
| Porosity (%)                                                  | 35         | 52         |
| Mean Pore Size (m)                                            | N/A        | 1.3 E-05   |
| Number of inlet cells                                         | 34,636     | 8,659      |
| Catalyst washcoat                                             | Pt alloy   | Pt         |

The layout of the exhaust system, which is designed to give flexibility during experimentation, is shown in Figure 1. The exhaust system includes two routes for the exhaust to flow through. The advantage of using two routes for the exhaust gas is to increase the consistency of the flow of the exhaust through the aftertreatment system. The line to the aftertreatment system is designated the trapline and the by-

pass line is the baseline. During ramp-up of the system to a specific engine load and speed, the exhaust is initially diverted to the baseline. Once speed, load and turbo-out exhaust temperature of the engine have stabilized, the exhaust gas is diverted to the trapline. This provides more consistency in the flow of exhaust through the aftertreatment device. Pneumatic valves are used for controlling the exhaust flow path. More information on the layout of the test cell can be found in [reference \[7\]](#). Sampling ports for gaseous concentration measurement and particle size distribution are mounted to the can upstream of the DOC (UDOC), downstream of the DOC (DDOC), and downstream of the CPF (DCPF). Differential pressure transducers for pressure drop measurement across the DOC, CPF and the laminar flow element (LFE) are also shown in the schematic.

<[figure 1](#) here>

An AVL AMA 4000 exhaust gas analyzer was used for gaseous measurements. It measures hydrocarbons (HC), NOx (NO<sub>2</sub> + NO), CO, CO<sub>2</sub>, and O<sub>2</sub>. The FID for measuring HC emissions and CLD for measuring NOx emissions are heated, while the other analyzers are not. Engine out PM concentrations were measured directly by hot sampling from the raw exhaust onto 47 mm glass fiber filters (Pall Corp., MI) using a Manual Sampling Train stack-sampler (Anderson Instruments Inc., GA). More information on this procedure is available in [reference \[8\]](#). Temperature measurements were made using K type thermocouples (Omega, NY). Stainless steel sheath thermocouples with sheath diameters of 3, .8, and .5 mm (0.125, 0.032 and 0.020 inch) were used in the can, CPF and DOC channels respectively. A detailed description of the instrumentation and sampling techniques used during this study are explained in detail in [references \[8\], \[9\] and \[10\]](#). The CPF weight (tare weight) was measured using a heavy duty solution balance (Ohaus, NJ) with a readability of 1 gram for the first four experiments and with an Ohaus Ranger RD35LM with digital readout and 0.1 gram readability for the remainder of the experiments.

Particle size distribution (PSD) was measured using a Scanning Mobility Particle Sizing (SMPS) system which combined four individual components. Three of the instruments are manufactured by TSI Instruments Inc. and include a model 3065 low flow thermodenuder, model 3071A electrostatic classifier (EC) and a model 3025A condensation particle counter (CPC). The fourth component is a mini dilution system of an in-house design. The exhaust gas for the SMPS system was diluted using filtered compressed air heated to 200°C using an average dilution ratio of 10:1 (air/exhaust). Secondary conditioning of the diluted exhaust is provided by the thermodenuder which removes volatile components before delivering the sample to the EC [\[11\]](#). After being processed through the classifier, the particles are

then routed to the CPC which measures the size distribution characteristics of the sample [\[12\]](#).

Data was collected with the thermodenuder heated to a temperature of 230°C; this provides for a more consistent sample by ensuring that hydrocarbons and soluble organic fraction present in the sample remain in gaseous form [\[13\]](#). These entrained molecules are then removed by the activated carbon used within the thermodenuder. The acquisition of the PSD was acquired with the software programmed with an up-scan time of 180 s and a down scan time of 60 s. The diluted sample flow rate used during this study was 0.7 lpm. Corrections were made to the data for losses due to the use of the thermodenuder using methods developed in [reference \[11\]](#) and to account for the dilution ratio used during sampling. This procedure provides the PSD weighted by number or volume for the selected sampling location.

The soy-based biodiesel blend fuels used in this study were tested to determine their properties. The results can be seen in [Table 4](#). Summer-grade ULSD fuel with 15 ppm or less sulfur content was used from the same supplier as used by [reference \[1\]](#). The values for ULSD from [reference \[1\]](#) are shown in [Table 4](#).

Table 4. Fuel properties

|                                |          | ULSD  | B5    | B20-1st Batch | B20-2nd Batch |
|--------------------------------|----------|-------|-------|---------------|---------------|
| API Gravity @ 60F              |          | 36.2  | 37.0  | 35.0          | 33.8          |
| Sp. Gravity @ 60F              |          | 0.84  | 0.84  | 0.85          | 0.86          |
| Viscosity (mm <sup>2</sup> /s) |          | 2.30  | 2.40  | 2.77          | 2.57          |
| Total sulfur (ANTEC)           |          | 8 ppm | 8 ppm | 8ppm          | 8 ppm         |
| Cetane Index                   |          | 46.2  | 46.1  | 46.5          | 43.6          |
| Sim Distillation               | IBP (°F) |       | 353   | 352           | 358           |
|                                | FBP (°F) |       | 650   | 656           | 656           |
| Karl Fisher for Water (ppm)    |          |       | 28    | 59            | 169           |
| ICP for Metals                 |          |       |       |               | <1 ppm*       |
| Bio Diesel %                   |          |       |       |               | 20.1          |
| Heat of Combustion (MJ/kg)     | HHV      | 47.4  | 45.5  | 44.5          | 44.2          |
|                                | LHV      | 44.9  | 43.2  | 42.0          | 41.8          |

\*- all elements less than 1 ppm

## TEST PROCEDURE AND MATRIX

The general procedure used for these experiments is shown in [Figure 2](#). The first step is to remove (clean) existing PM from the filter by running at high loads and dosing fuel into the exhaust stream to achieve a CPF inlet temperature of 600°C. This temperature is maintained for 30 minutes to ensure a clean CPF. The doser is shut off, the pressure drop across the filter is allowed to stabilize, and the exhaust is switched to the baseline within one minute from the end of injection. The engine is then ramped down and the CPF is removed from the trapline and weighed (designated m<sub>C</sub> in [Figure 2](#)). The process of weighing the CPF was later discovered to be more dynamic than originally thought and requires very consistent preconditioning and measurement techniques. This process is a crucial step in attaining accurate measures of the amount of PM in the filter, and a discussion of the CPF weighing procedure can be found in [Appendix A](#). The CPF is then

returned to the trapline and loading of the filter is performed at 2100 rpm and 20% load. During loading, gaseous emissions are continuously collected while switching between locations. PM concentrations are measured at least three times upstream of the DOC, and once downstream of the CPF if time permits. Previous data on PM concentrations, passive oxidation rates and filtration efficiency is used to estimate the required amount of time needed to achieve a certain level of PM loading in the CPF. The experiments in this study were performed at a PM loading level of 2.2 g/L.

After the CPF is loaded for the predetermined period of time, it is removed from the trapline and weighed again to determine how much PM has been deposited ( $m_L$  in Figure 2). This data, along with the exhaust flow rate and measured PM concentrations, is used to determine the passive oxidation rate in the CPF. The procedure for determining the respective values in the mass balance and tables with the mass balances for all the experiments are included in Appendix B. The CPF is returned to the trapline for active regeneration. After the engine is warmed-up, the exhaust is switched to the trapline and after two minutes the engine is ramped up to 40% load. Gaseous emissions, fuel and air flow rates, and PM concentrations are recorded, then after 5-10 minutes the fuel dosing into the exhaust is commenced at a predetermined duty cycle of the injector. The duty cycle is adjusted as needed to attain the desired CPF inlet temperature, and active regeneration is performed for a predetermined period of time. After the doser is stopped, the engine is run for two additional minutes at 40% load and then ramped down to 20% load while running in the trapline. After the average temperature of the CPF has dropped below 290°C, the exhaust is switched to the baseline and the CPF is weighed once again ( $m_R$  in Figure 2). Post loading is performed for one hour at the same conditions as loading to determine differences in the performance of a clean and partially regenerated CPF. The final weight of the CPF at the end of post loading is also measured ( $m_{PL}$  in Figure 2). As seen in Figure 2, this is the end of one experiment and the process starts over with a clean out to remove the PM in the CPF from post-loading.

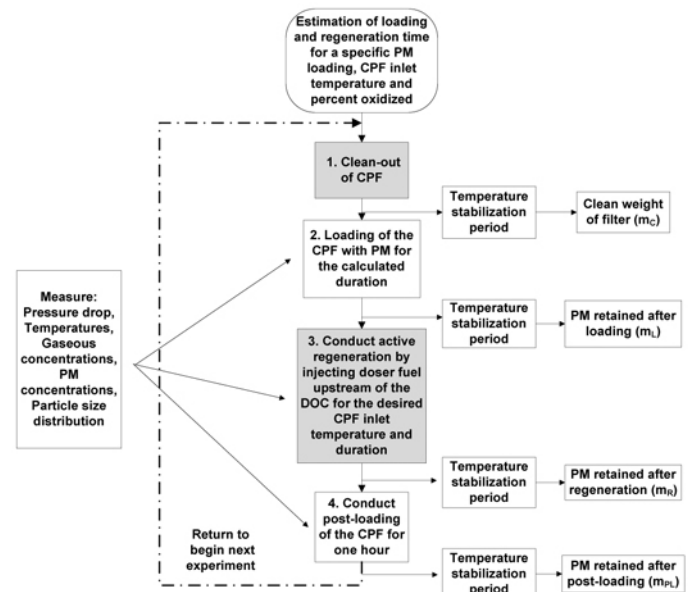


**Figure 2. Diagram of experimental process for clean out, loading, active regeneration and post-loading (modified from Chilumukuru et al. [1])**

As stated previously, this study is a continuation of a study performed on the active regeneration characteristics of ULSD [1]. The first tests with B20 were performed at the lowest regeneration temperature with the same duration of active regeneration used in that study (525°C CPF inlet temperature, 22 minutes). After examining the pressure drop across the CPF during the regeneration, it was apparent that a majority of the PM had been oxidized in the first 4-5 minutes and that a nearly complete regeneration had been performed. This data with nearly complete regeneration is not very useful because the amount of PM in the CPF is not much greater than the accuracy of the scale, so the error associated with determining the oxidation rates is large. As a result, the data from these tests is not reported in this paper.

The test matrix that was used to determine the active regeneration rates is shown in Table 5. Tests were performed at different CPF inlet temperatures to determine how the reaction rate changes with temperature. Two different percent oxidized targets were also used. This is to examine if the reaction rate is constant or if it changes as the reaction progresses. The test numbers represent the chronological order of the experiments for each fuel. The shaded cells are the runs from the previous study by Chilumukuru et al. [1], and their numbering scheme was used for those runs. Two repeats were performed in this study at the same conditions as the repeated experiment from Chilumukuru et al. [1] (ULSD, 2.2 g/L loading, 525°C CPF inlet temperature, 70% oxidized) to establish the repeatability of experimentation between test programs.

**Table 5. Test matrix showing tests reported by chronological order for each fuel and tests by Chilumukuru et al [1] in shaded cells (all reported tests are at a PM loading level of 2.2 g/L).**

|            | CPF Inlet Temperature (°C) |    |     |     |                      |    |     |    |     |    |
|------------|----------------------------|----|-----|-----|----------------------|----|-----|----|-----|----|
|            | 475                        |    | 500 |     | 525                  |    | 550 |    | 600 |    |
| % Oxidized | 40                         | 70 | 40  | 70  | 40                   | 70 | 40  | 70 | 40  | 70 |
| ULSD       |                            |    |     |     | 2,6,10,13<br>rep A,C | 11 | 4   |    | 8   |    |
| B5         |                            |    | 2   | 4   | 1                    |    | 3   |    |     |    |
| B20        | 6                          | 5  | 4   | 7,8 | 3                    |    |     |    |     |    |

## DATA ANALYSIS

After the start of the doser injector, the temperature in the CPF increases, but does not reach steady state for approximately one minute. Additionally, there is a time delay after the injector is stopped before the CPF temperature drops below its elevated state. This is seen in [Figure 3](#). Following the same method used by Chilumukuru et al. [1], it was decided to consider only the portion of the regeneration where the temperatures are nearly steady state for the calculations of the reaction rate. The main portion of the regeneration has a global reaction rate  $RR_o$ , which corresponds to the average temperature in the CPF. To define the start of the regeneration, a temperature is calculated that would give a reaction rate of one-half of  $RR_o$ . This temperature is the effective temperature  $T_{eff}$ , and the reaction is considered to be occurring as long as the average CPF temperature,  $T_R$ , is greater than  $T_{eff}$ . The effective time  $t_{eff}$  is the period of time during which  $T_R$  is greater than  $T_{eff}$ , and is always shorter than  $t_a$ , the duration of fuel injection. The time before and after this period is considered the ramp-up and ramp-down periods and it is assumed that no measureable oxidation of PM occurs during these times. However, the amount of PM deposited during these times is accounted for in determining the initial and final corrected PM masses ( $m_{L1}$  and  $m_{R1}$ ) for the regeneration. A schematic of the mass corrections is shown in [Figure 4](#). Determining the times, temperatures and masses becomes an iterative process. A temperature is assumed for  $T_{eff}$  and only the data where  $T_R > T_{eff}$  is considered. The starting and ending mass are calculated, and the average CPF temperature during that period is calculated. These values are entered into the reaction rate equations, which are discussed in the following paragraph, and a better estimate of  $T_{eff}$  is found. This requires the window of data to be modified and the values recalculated. This process is repeated until it converges.

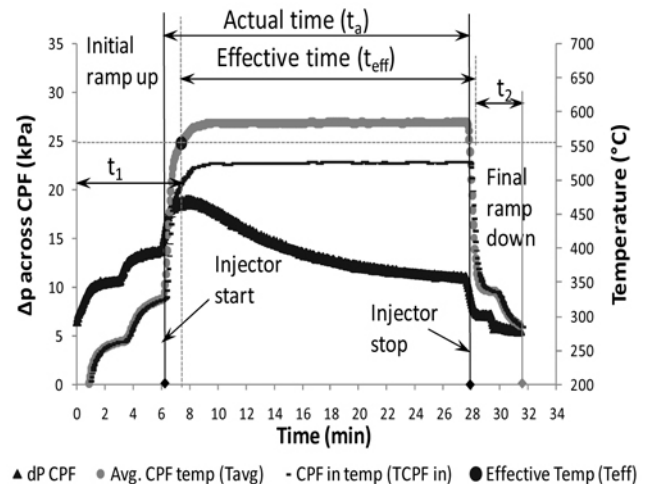


**Figure 3. Diagram of effective temperature, actual and effective time for active regeneration [1].**

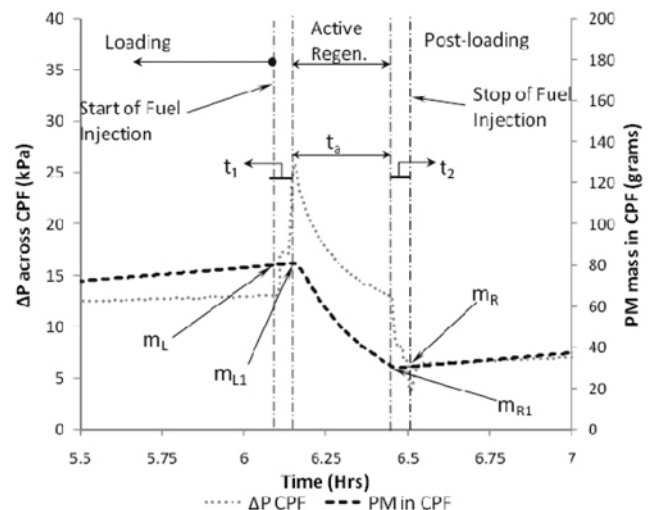


**Figure 4. Time and mass corrections for ramp-up and down during active regeneration [1].**

The oxidation rate of the PM is proportional to the amount of PM available in the filter at the time,  $m(t)$ , and the global reaction rate of the PM, as shown in [Equation 1](#).

$$\frac{dm_{ox}}{dt} = RR_o \cdot m(t)$$

1

$RR_o$  = Global reaction rate of PM in the CPF [1/s]

$m(t)$  = PM in the CPF at time  $t$  [g]

The oxidation of PM in the CPF is considered to occur by two means. [Equation 2](#) has two terms, one that exponentially oxidizes the PM that was in the CPF at the start of

regeneration, and another term that oxidizes the engine-out PM that enters the CPF during the regeneration.

$$m_{R1} = m_{L1} \cdot e^{(-RRo \cdot t_{eff})} + \frac{Q \cdot C_{in} \cdot \eta_f}{RRo \cdot 1000} \cdot [1 - e^{(-RRo \cdot t_{eff})}]$$

2

$Q$  = Exhaust volumetric flow rate, [std. m<sup>3</sup>/sec (25°C, 1 atm)]

$C_{in}$  = Engine out PM concentration, [mg/std.m<sup>3</sup>]

$\eta_f$  = Filtration efficiency of the filter, [fraction]

$t_{eff}$  = Effective time of active regeneration, [seconds]

$m_{R1}$  = Corrected PM mass retained in the CPF at time  $t_{eff}$ , [g]

$m_{L1}$  = Corrected PM mass in CPF before start of active regeneration, [g]

The oxidation of PM in the range of 400 to 700°C is thermally dependent and follows an Arrhenius type behavior [14]. The oxygen concentrations in this study were consistent, so the Arrhenius equation 3, was used to determine the activation energies and pre-exponential coefficient in the same method used by reference [1].

$$RRo = A \cdot e^{\left(\frac{-E_a}{R \cdot T_R}\right)}$$

3

$A$  = Pre exponential factor; [1/s]

$E_a$  = Activation energy, [J/gmol]

$R$  = Universal gas constant, [J/gmolK]

$T_R$  = Average temperature in CPF during active regeneration, [K]

The thermocouple layout in the CPF, as seen in Figure 5, was carefully chosen to give the best estimate of the volume averaged temperature in the CPF and the shape of the temperature gradients. One set of the thermocouples are inserted approximately 32 mm down the inlet channels, and three sets are inserted into the outlet channels at locations of 153, 216, and 273 mm from the inlet face. The radial locations of the thermocouples were chosen by dividing the face of the CPF into three rings of equal area. Thermocouples are placed in the centroids of each of the regions. The temperatures from the three thermocouples can be averaged to determine the average temperature at each axial distance. These averages are then plotted, as can be seen in Figure 15. A linear trend line is fit to the axial temperature profiles and the value at the midpoint distance is taken as the average CPF temperature,  $T_R$ . This calculation is equivalent to integrating the temperature profile and gives a good estimation of the volume averaged temperature of the CPF.

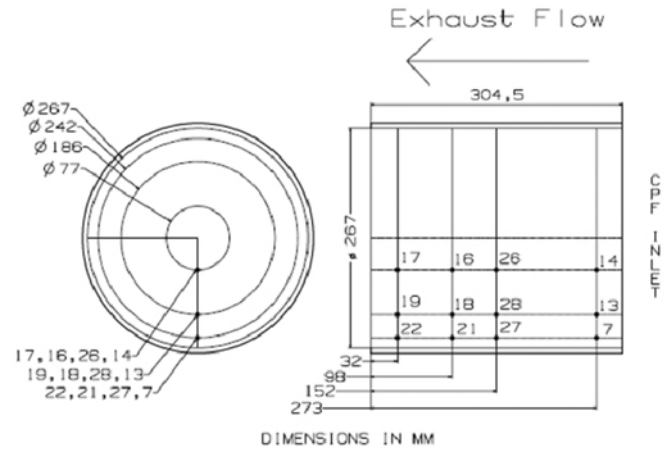


Figure 5. Thermocouple layout in the CPF showing radial and axial locations

## EXPERIMENTAL RESULTS

### LOADING

#### Gaseous emissions

Average gaseous emissions concentrations during loading are presented in Figure 6. The concentrations for all the runs in this study are presented in Table 14, Table 15, Table 16 in Appendix C. The engine-out gaseous emissions during all portions of the test procedure varied slightly between the three different fuels that were tested. The HC concentrations at 20% load were 10-15% lower with B20 as compared to ULSD. The NOx values were similar between blends on average, but varied considerably between tests. This can be attributed to differences in the engine operation with variation in the ambient conditions. The ambient conditions in the test cell are not controlled, and the B20 tests were all performed during the winter when the air was cool and dry, while the B5 tests were performed during the spring and start of summer, when it was warmer and more humid. This makes it difficult to conclude if there are any differences in gaseous emissions and PM passive oxidation characteristics between blends, as the change from one fuel to another occurred at the same time as these systematic changes in test cell conditions. As can be seen in Figure 6 and is discussed further in Appendix D, the variation in NOx concentrations between tests with one fuel was greater than the variation in average concentrations between fuels.

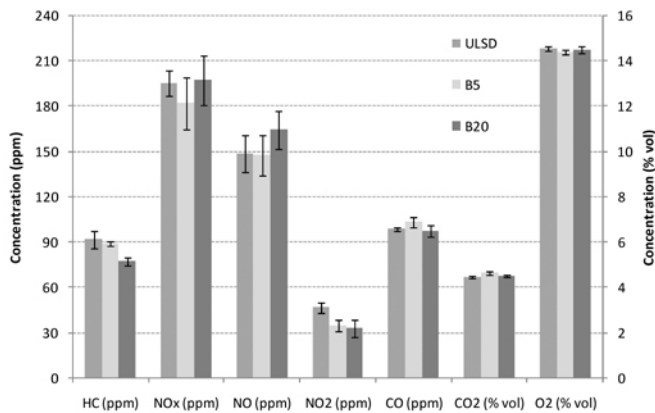


**Figure 6. Average gaseous emissions during loading for ULSD, B5, and B20**

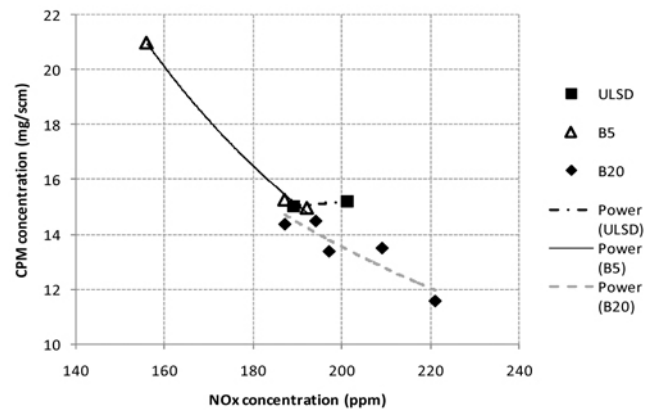


**Figure 7. NOx to PM trade-off plot for the reported runs in this study.**

## PM CONCENTRATIONS

The observed PM concentrations at 2100 rpm and 20% load varied from 11.5 to 14.5 mg/scm for B20, from 15.0 to 21.0 mg/scm for B5, and were 15.1 mg/scm for both the ULSD repeats. Variation was seen between fuels as expected, and between tests with the same fuel. Similar to the NOx emissions, the variation between tests with the same fuel was greater than the variation between fuels. As can be seen in Table 6, the COV between samples from a single test was low, giving confidence in the repeatability of measurements. As an additional check for the variations, especially between B5 experiments, a NOx to PM tradeoff plot was constructed, as can be seen in Figure 7. The NOx and PM values were inversely related for the same fuel, as expected. As is discussed in Appendix D, additional testing was performed to test the hypothesis that this variation was the result of differences in test-cell conditions between experiments, and the results supported that theory.

**Table 6. Average PM concentrations during loading for reported runs**

| Test       | Average PM concentration (mg/scm) | COV (%) |
|------------|-----------------------------------|---------|
| BD20-3     | 13.5                              | 3.1     |
| BD20-4     | 13.4                              | 4.4     |
| BD20-5     | 14.4                              | 2       |
| BD20-6     | 14.5                              | 4.6     |
| BD20-7     | 13.1                              | 2.8     |
| BD20-8     | 11.6                              | 5.4     |
| BD5-1      | 15.3                              | 3.5     |
| BD5-2      | 14.9                              | 5.3     |
| BD5-3      | 16.4                              | 3.7     |
| BD5-4      | 21                                | 2.6     |
| ULSD rep A | 15.1                              | 1.1     |
| ULSD rep C | 15                                | 4.3     |

## PARTICLE SIZE DISTRIBUTION

Data were taken during each of the individual tests specified within the test plan shown in Table 6 to determine the particle size distribution (PSD) exiting the engine exhaust. The sampling locations were UDOC, DDOC, and DCPF during loading and post loading. Sampling was performed only DCPF during active regeneration due to time limitations. Averages of these data sets were compiled for loading and are shown in Figure 8 and 9 weighted by size and volume respectively. PSD with the three different fuels exhibited similar shapes with small shifts of the apex dependent upon the specific type of fuel being used.

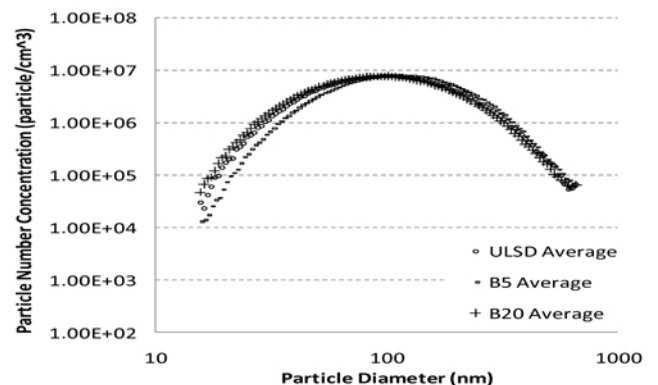


**Figure 8. Comparison of engine-out Particle Size Distribution weighted by number during loading for ULSD, B5 & B20**

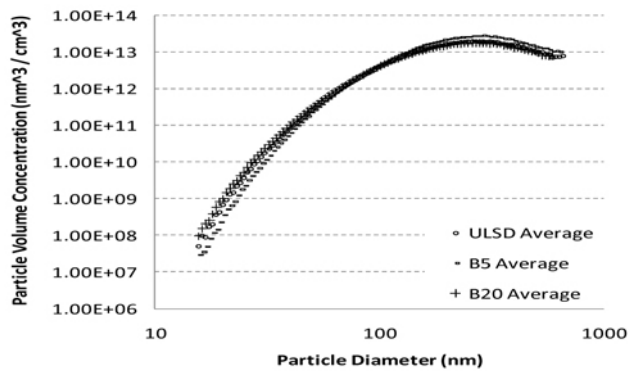


**Figure 9. Comparison of engine-out Particle Size Distribution weighted by volume during loading for ULSD, B5 & B20**

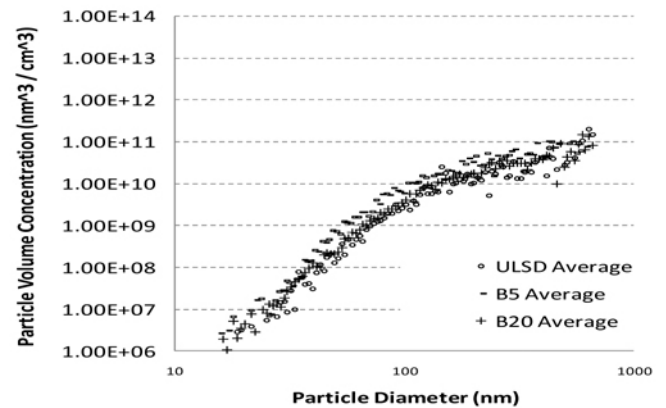


**Figure 11. Comparison of Particle Size Distribution DCPF weighted by volume during loading for ULSD, B5 & B20**

Results obtained downstream of the catalyzed particulate filter (DCPF) during loading can be seen in [Figure 10](#) and [11](#) weighted by number and volume respectively. Once again the PSD exhibited similar shapes with small shifts of the apex dependent upon the specific type of fuel being used. Results obtained DCPF during active regeneration were similar to loading values and as such, for brevity, will not be included. Further information on the PSD can be found in [Appendix E](#).

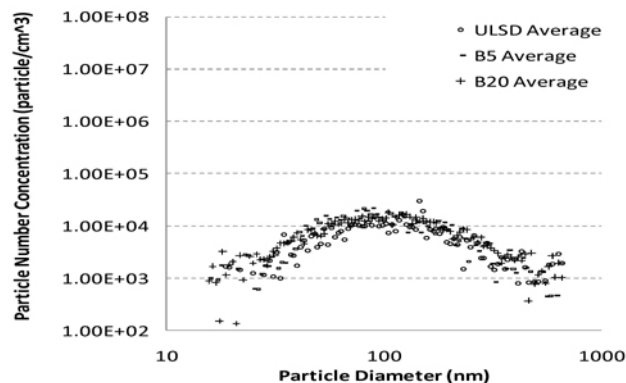


**Figure 10. Comparison of Particle Size Distribution DCPF weighted by number during loading for ULSD, B5 & B20**

## CPF PRESSURE DROP

The different blends of biodiesel showed similar delta pressures across the CPF during loading for a given amount of PM loading in the CPF, as seen in [Figure 12](#). However, as stated, the engine-out PM concentrations were lower for the B20 testing, so the amount of time required to deposit the target amount of PM in the filter was longer. This results in a longer time period before regeneration is necessary, which is beneficial for minimizing the fuel penalty associated with the use of an aftertreatment device. Also to note on this figure is that the pressure drop for a given PM loading is lower for post-loading than it is for loading by approximately 1.5 kPa. This is similar to the results found by Chilumukuru et al. [1]. As determined in the modeling work by Arasappa et al. [15], this is dependent on the amount of cake layer that is left in the filter after regeneration. The overall pressure drop across the CPF can be split into two parts, the pressure drop across the wall and the pressure drop across the cake layer. The pressure drop across the wall is significantly greater than the pressure drop across the cake layer, and also increases considerably as PM is deposited in the wall. This is one of the benefits of only partially regenerating the CPF. The PM in the wall oxidizes first, and if a cake layer is left it filters the PM out of the exhaust before it can be deposited in the pores of the substrate. This leads to a lower pressure drop across the wall and lower overall pressure drop across the CPF.