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Exhaust Tailpipe Fuel Spray Optimization and Fuel Usage Rates for Operating an Exhaust Aftertreatment System on a Heavy-Duty Diesel Engine Powered Vehicle

James McCarthy, Jr.*, Daniel Bamber, Steve Ambrose
Eaton Corporation
26201 Northwestern Highway
Southfield, MI 48076

Abstract
Exhaust tailpipe fuel injection is required for many diesel engine aftertreatment systems including diesel particulate filter (DPF) systems, fuel reforming systems and lean NOx trap (LNT) systems. The design objective of this work was to develop an exhaust tailpipe fuel injection spray that promoted high aftertreatment conversion efficiencies with low fuel usage. A fuel injection system utilizing a pulse-width modulated (PWM) pressure swirl atomizer was first evaluated in a spray laboratory using drop size and spray patternation diagnostic equipment. The fuel system was later evaluated as part of an aftertreatment system consisting of a fuel reformer, LNT, DPF and selective catalytic reduction (SCR) catalysts. The aftertreatment system was sized to meet EPA 2010 emission standards for an on-highway heavy-duty diesel engine. A high turn-down ratio injection system (16.5:1) with a flow range from 30 to 500 grams per minute was developed for this application. This fuel flow range was required to operate the fuel reformer in both lean and rich modes. Low fuel flow rates were used during lean mode operation for catalyst heating and DPF regeneration. During rich mode operation, diesel fuel was converted to hydrogen and carbon monoxide in the fuel reformer. The fuel spray consisted of drop Sauter mean diameters (SMD) that ranged between 55 and 70 microns within a fuel supply pressure that ranged between 4.8 and 7.0 bar. The fuel injection and aftertreatment systems were evaluated using a heavy-duty diesel engine during dynamometer and on-highway vehicle testing. Test results showed the ability to meet EPA 2010 emission levels with low fuel usage rates.

* Corresponding Author: JimMcCarthy@Eaton.com

Introduction

The Environmental Protection Agency (EPA) issued emission legislation for future diesel engine vehicles. Strict emission standards will be required for on-highway vehicles in 2010 while final Tier 4 emission standards for off-highway vehicles will be required in 2014. The feasibility of an aftertreatment system to meet a final Tier 4 emissions standard of 0.4 g/kW-hr NOx has been addressed [1, 2]. The 0.4 g/kW-hr NOx standard is applicable for engines having rated power levels above 56 kW. This paper addresses the development and demonstration of a tailpipe fuel doser in both a NOx and particulate aftertreatment system.

The aftertreatment system consists of a fuel dosing system, mixing elements, fuel reformer, lean NOx trap (LNT), diesel particulate filter (DPF), and selective catalytic reduction (SCR) catalyst arranged in series. A sample configuration of this system is shown in Figure 1. Similar systems using LNT and SCR technology without a fuel reformer are cited in literature [3, 4]. A fuel reformer is utilized to generate hydrogen (H_2) and carbon monoxide (CO) from injected diesel fuel. These reductants are used to regenerate and desulfate the LNT catalyst. NOx emissions are reduced using the combination of the LNT and SCR catalysts. During LNT regeneration, ammonia (NH_3) is intentionally released from the LNT and stored on the downstream SCR catalyst to further reduce NOx that passed through the LNT catalyst. This approach converts the drawbacks of the single leg LNT approach (low conversion during regeneration and NH_3 slip) into an advantage while remaining independent of any urea infrastructure since diesel fuel is the only reductant [1, 5-9].

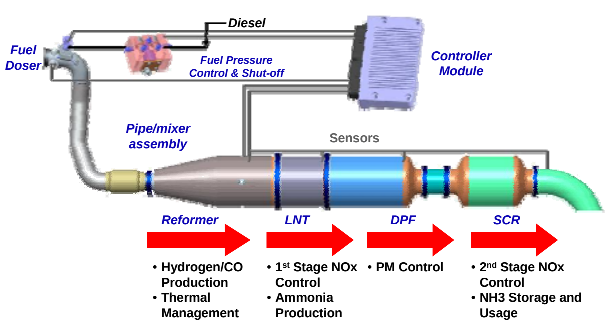

Figure 1. Aftertreatment system layout.

The objective of this work was to develop a fuel injection system that is appropriate for the aftertreatment system, along with aftertreatment systems requiring only a DPF. A fuel reformer is used in the aftertreatment system which cycles from lean to rich operation. An overview of the fuel reformer operation is provided.

The fuel reformer has two main functions during regenerations, 1) to consume the residual oxygen in the exhaust gas stream, and 2) to convert remaining reformer fuel to the reductants, H_2 and CO. Operation of this reformer is cited in literature [1, 5-11]. Typical reformer control during a high engine load operation on a medium heavy duty engine is shown in Figure 2 [1]. Fuel is injected into the reformer to warm the catalyst to its proper operating temperature. Engine out oxygen is then reduced via engine control to a lower oxygen operating mode from 7.2% to 3.2%. A higher fueling rate is commanded to consume the remaining oxygen as depicted by the tailpipe oxygen dropping to zero. This higher rate creates a rich condition where reformate is produced, depicted by the predicted CO and H_2 profiles. The reformate is key to regenerating and desulfating the downstream LNT.

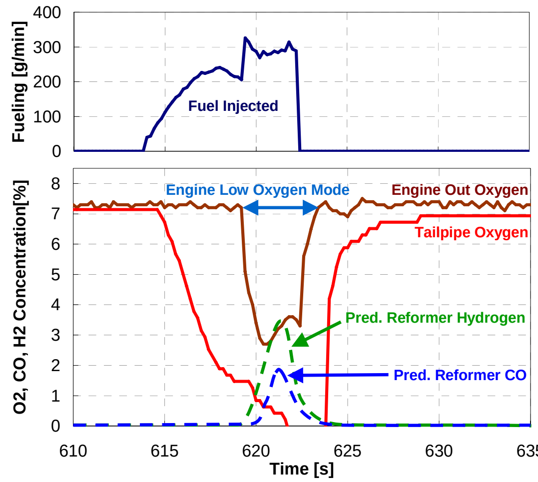

Figure 2. Typical reformer operation [1].

The aftertreatment system described requires a low fuel injection rate for warming up the fuel reformer and a higher fuel injection rates for rich operation. Aftertreatment systems have been procured for many engine sizes. The example provided in Figure 2 was demonstrated on a medium-heavy duty diesel engine. Systems for heavy-heavy duty diesel engines have also been procured requiring higher fuel flow rates.

This paper describes a fuel injection system suitable for light, medium and heavy duty diesel aftertreatment applications. The fuel injection system is described along with the fuel flow ranges for each system. The experimental testing is described along with fuel injection results. Finally, results from a vehicle demonstration are provided showing efficient fuel economy for the aftertreatment system.

Fuel Injection System Overview

The fuel injection system consists of a fuel injector coupled with a fuel manifold assembly (FMA). The fuel injector is a pressure swirl atomizer that has a pintle that acts as an internal shutoff that is controlled using an electromagnetic solenoid. The FMA provides fuel to the fuel injector while controlling pressure.

A variety of fuel injectors have been developed for various fuel flow ranges and pressures. Flow ranges include 10 to 250 g/min, 30 to 500 g/min, 30 to 750 g/min and 50 to 1000 g/min. Flow ranges up to 750 g/min have been developed using fuel supply pressures of 4.8 bar. The higher flow range can be accomplished using two fuel injectors (30 to 500 g/min) at 4.8 bar or a single fuel injector having a fuel supply pressure of 7.0 bar. The system consisting of the 30 to 500 g/min fuel injector is described in this paper.

Figure 3 shows the fuel injector including the fuel lines and electrical connections. Fuel is supplied to the injector near the nozzle. The injector is cooled by fuel that continuously flows through the injector. Fuel that is not used for injection exits the injector at the top. Fuel is injected from the nozzle by actuating the solenoid with a pulse width modulated (PWM) signal. A typical signal is operated at 10 Hz frequency using a 12 Volt power source. The injector is typically operated from a 5 to 95% duty cycle. These duty cycles correspond to a fuel flow rate of 30 to 500 g/min.

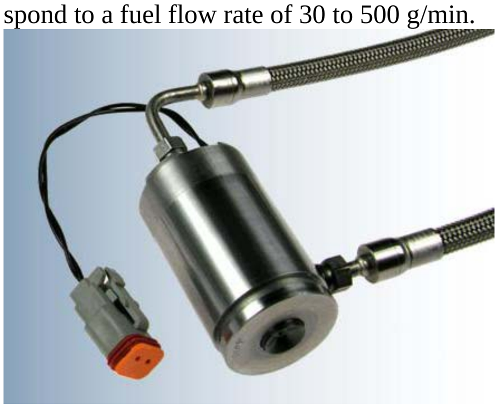

Figure 3. Fuel Injector

The FMA is shown in Figure 4. The FMA is an integrated unit comprising the components of the Fuel Control Circuit (FCC). The following components make up the assembly; a 6061-T6 Aluminum fuel distribution block, an optional "spin on" 20-micron fuel filter, a two-way normally closed proportional flow control valve, a special two-way normally closed fuel cutoff valve, a pressure sensor, check valve, and manifold fittings (4) for the various mating fuel hose connections. The manifold block footprint is approx. 118mm x 118mm x 45mm while other footprints have been customized. The assembly can be located on a vehicle chassis frame rail or within the vehicle engine compartment.

The purpose of the FMA is to serve as a fuel control conduit between a Fuel Pressure Circuit (FPC) and an Injection-Cooling Circuit (ICC). The manifold assembly serves three functions:

- Manage fuel supply pressure to the injector within the ICC.
- Provide leak detection capability within the ICC to assess the amount of any external fuel leakage.
- Provide fuel shut-off capability to the injector in the event that ICC leakage exceeds a predetermined mass fuel flow rate determined by the customer specific application.

Figure 4. Fuel Manifold Assembly (FMA)

The FMA provides a means to shut-off fuel if a leak is detected. A leak detection method and circuit was developed to discern small amounts of fuel leakage in excess of 1 g/min. A pressure sensor was used in conjunction with the fuel cut-off valve, check valve, and necessary control logic to monitor leakage via pressure decay within the ICC. A special fuel cut-off valve was developed that exhibited low leakage characteristics. This electro-hydraulic valve was utilized on a fuel distribution manifold assembly to shutoff fuel flow to the dosing fuel injector in the case that fuel leakage occurs.

Fuel Injector Development

An aftertreatment fuel injector was developed for exhaust aftertreatment applications. The goal of the development was to provide an injector with a turn-down ratio greater than 15:1, using a supply pressure that can be produced by typical low pressure gear pumps available on diesel engines. Turn-down ratio is defined as the ratio of the maximum to minimum flow rate. Both low and high flow rates are required by the fuel reformer, LNT and DPF systems at fuel supply pressures on the order of 4.8 bar.

A pressure swirl atomizer was chosen to meet the design goals for the aftertreatment application. The supplied fluid travels through a group of channels that are arranged tangentially to the perimeter of a swirl chamber. The outlet orifice of this chamber is on the axis of the injector so the entering fluid swirls in a circular motion and increases in speed as it moves towards the exit orifice. The fluid swirls fast enough at the exit orifice to create an air core in the center of the orifice. The presence of the air core forces the exiting fuel to form a thin circular sheet. Aerodynamic forces break the fluid sheet into drops after it exits the injector. Proper atomization for a given flow rate is achieved by adjusting the injector geometry to control the size of the air core.

The injector uses additional diesel fuel flow to remove heat that conducts to the injector from the exhaust pipe. This fuel flows from the pressure swirl atomization chamber, through the solenoid and out the coolant flow return port. The coolant flow maintains the injector temperature within the rated temperature range without requiring a secondary cooling medium.

A PWM type solenoid was chosen as the method of actuation in controlling atomizer nozzle flow rate. The flow rate from the injector is proportional to the solenoid duty cycle input. This feature provides flexibility to provide a variety of fuel flow rates within the operational flow range of the injector. A highly linear flow rate as a function of duty cycle can be achieved using PWM control. This is advantageous for characterizing an injector and implementing simple control equations to calculate the duty cycle to accurately reproduce the required injector flow rate.

Experimental Setup

The spray characteristics of the fuel injection system were quantified using laser diagnostics to report drop size and spray patternation. High speed videos were also used to better understand the fuel spray. Two different types of non-intrusive diagnostic setups were used to characterize each injector. The fuel spray was characterized using a Malvern Spraytec, En'Urga SETscan Optical Spray Patternator and spray visualization equipment. The Malvern Spraytec will be referred to as the Spraytec throughout the paper. Likewise, the SETscan Optical Spray Patternator will be referred to as the SETscan.

Figure 5 shows the setup of the spray diagnostic test stand. The injector is supported by a framework that supports the injector over the collection tank. This framework is attached to a motorized linear slide that allows the injector to be translated during injection. The injector is centered over the SETscan and held stationary while collecting patternation data. The injector is translated so that the spray scans across the Spraytec laser beam while collecting drop size distribution data. A suction fan and collection tank draws the fuel spray downstream of the laser diagnostics to prevent splashing and re-circulation back into the data collection plane. The height of the injector is manually adjusted to set the distance for data collection.

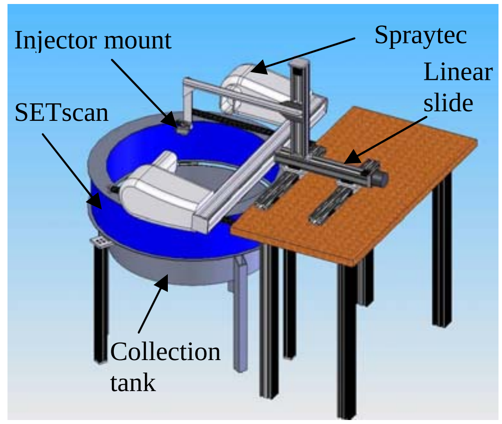

Figure 5. Spray Diagnostic Setup

A Spraytec was used to collect drop size distribution data from the fuel injection system. The Spraytec reports the drop size distribution by measuring diffraction of light caused by a drop passing through a laser source. The diffracted laser light is collected on a series of concentric light sensors at a rate of 2500 samples/sec. The optical data for each sample is converted to an instantaneous drop size distribution and volume concentration. The spray is traversed across the Spraytec laser at a constant rate of 5 mm/s such that the overall drop size distribution is reported as an average of the instantaneous drop size distributions, weighted by the volume concentration. The injector testing is performed by scanning the injector spray across the laser source at a distance of 76.2 mm (3 in.) This method equally samples all portions of the spray and provides a drop size distribution that is representative of the engine spray [12, 13].

The characteristic drop sizes and volume fractions were calculated for the sprays. The Dv(0.10), Dv(0.50), Dv(0.90) drop diameters were calculated from the overall drop size distribution. These three parameters represent the spray drop size where 10%, 50% and 90% of the cumulative spray volume are contained. The Sauter mean diameter (SMD) is an average drop size that represents the ratio of the spray volume to surface area. The overall volume fraction distribution for the spray was assessed to determine the drop size distribution over the spray volume. The spray data was evaluated at two key operating conditions. A low duty cycle of 10% was used to understand the spray characteristics while the injector pintle was opening. A high duty cycle of 90% was used to understand the spray characteristics during steady state operation.

The SETscan was used to discern the spray patternation from the fuel injection system. The SETscan uses the changes in the intensity of laser light projected through the spray from multiple directions to estimate surface area concentration of the spray at various locations. Unlike the Spraytec, the SETscan does not collect instantaneous data. Instead, it collects light intensity data for ten seconds and calculates a single time-averaged distribution. The spray patternation distribution has units of surface area per unit volume as a function of the 2D coordinates in the plane of the projected lasers.

A high speed video camera was used to capture images of the spray. These images were used to evaluate the formation of the spray as the injector pintle opened as discussed below. The videos provided insight into the visible spray regimes as the spray developed. An example of the spray transition between pressure atomization and pressure swirl atomization is described in the next section.

Injection System Development

Early development of the fuel injection system provided encouraging results coupled with opportunities for improvement. Results showed that the injection system produced two stages of performance. Pressure swirl atomization coupled with small drop sizes occurred once the injector pintle was fully open. However, during the transition stage while the pintle was opening, a spray having a smaller cone angle and larger drop sizes occurred (i.e., pressure atomization). Figure 6 shows an example of pressure atomization along with pressure swirl atomization. Pressure atomization occurred for 2-5 msec when the fuel exited the injector before fuel fluid swirl was completely formed. This led to a pulse of large, poorly distributed drops that were injected into the exhaust pipe. The design was altered to ensure pressure swirl atomization occurred as the pintle opened. The path that the coolant flow exited the swirl chamber was altered to maintain internal fluid swirl. Additionally, the geometry of the injector was altered to reduce the volume of the swirl chamber. These changes were effective in improving pressure swirl atomization upon opening the injector.

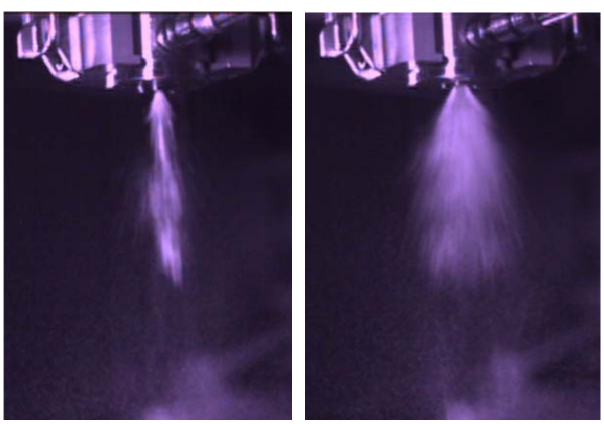

Figure 6. Pressure Atomization (left) and Pressure Swirl Atomization (right)

Spray Results

The spray characteristics from the fuel injection system are quantified in this section. The average drop size distribution is reported at both low and high duty cycle. Next, the volume fraction of the spray provides insight into the width of the drop size distribution. Additionally, the spray patternation profile is provided along with the fuel flow calibration.

Table 1 provides a summary of the time-averaged drop diameters for the injector spray when operating at 10% and 90% duty cycles with a 4.8 bar fuel supply pressure. The low duty cycle data is dominated by the spray that is formed while the pintle is opening. The high duty cycle data is dominated by the spray that is formed once the pintle is fully open. The table shows that the Dv(0.10), Dv(0.50) and SMD are smaller at the low duty cycle than at the high duty cycle. This demonstrates that the geometry changes made to eliminate the initial pressure atomization were effective in reducing the average drop size of the spray formed while the pintle is opening. In fact, the spray exhibits better atomization while the pintle is opening than when it is fully open. Dv(0.90) indicates that a few large drops formed while the pintle is opening. The injector geometry improvements yielded better atomization characteristics for both low and high duty cycles.

Table 1. Drop Diameters

Characteristic Drop Size	Average Diameter, microns	
	Low Duty Cycle (10%)	High Duty Cycle (90%)
Dv(0.10)	37.2	46.9
Dv(0.50)	66.4	73.8
Dv(0.90)	126.4	116.3
SMD	61.2	69.6

The volume fractions are provided in Figure 7 for low and high duty cycles. The low duty cycle volume fractions show a narrow bodied distribution below 100 microns with a tail in the higher drop sizes. The high duty cycle volume fraction shows a wider distribution with a smaller tail. The difference in the volume fraction tail is consistent with the slightly higher Dv(0.9) at low duty cycles. Other than this slight difference, the sprays are nearly identical, both having a tight drop size distribution with few drops above 200 microns. This similarity suggests that equal atomization characteristics are maintained across the injector operating range. The combination of the time-averaged drop size parameter and the volume fraction distribution supports that the injector geometry changes resulted in the desired atomization characteristics.

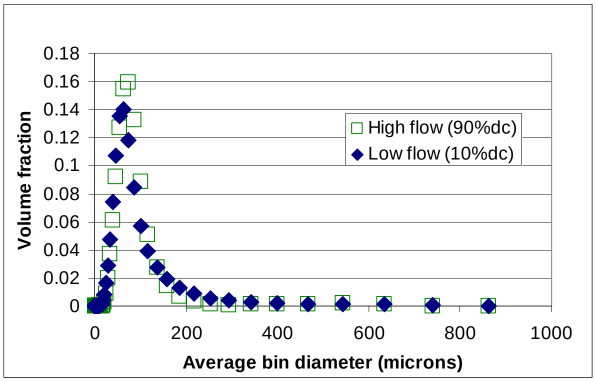

Figure 7. Volume Fraction

Figures 8 and 9 show the spray patternation in terms of surface area per unit volume. The spray is axisymmetric at both 90% duty cycle in Figure 8 and 10% duty cycle in Figure 9. The injector was operated at 4.8 bar injection pressure. The patternation decreases smoothly when moving from the center of the spray as expected from a pressure swirl atomizer. Typical pressure atomizers exhibit a higher central concentration at the center. The pintle opening effects on spray quality are minimized as evidenced by the patternation profiles at 10 and 90% being nearly identical.

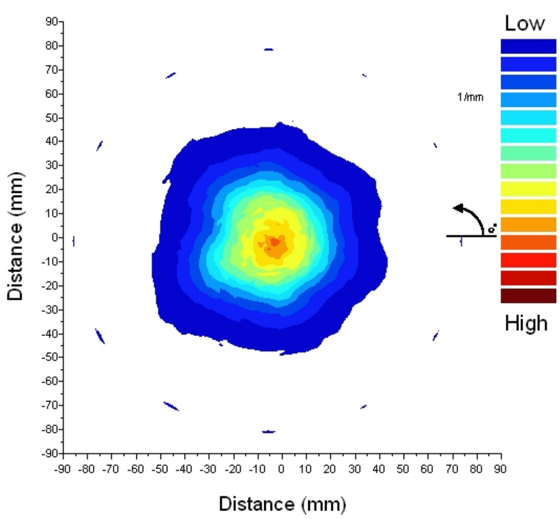

Figure 8. Spray Patternation at High Duty Cycle

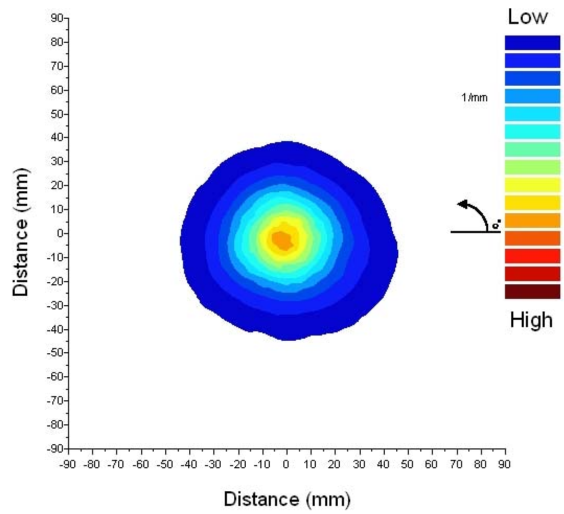

Figure 9. Spray Patternation at Low Duty Cycle

Figure 10 shows the mass flow rate as a function of duty cycle for 4.8 and 6.2 bar supply pressure. The injector is operated between 5 and 95% duty cycle. This flow rate yields a turn-down ratio of 16.5:1 at 4.8 bar. The turn-down ratio and maximum flow rate increases as the supply pressure is increased.

Figure 10. Fuel Flow Curve

Aftertreatment Dynamometer and Vehicle Results

The aftertreatment system was configured on a heavy duty vehicle and tested in a dynamometer test cell to characterize the aftertreatment system using the fuel injection system described. The aftertreatment packaging on the vehicle is described. Emission and fuel usage results are reported for the test cell. Vehicle and test cell fuel usage numbers are compared. Finally, the fuel usage for a typical DPF regeneration is reported.

The fuel injection system was utilized for an aftertreatment demonstration on a heavy duty vehicle. The aftertreatment system included a fuel reformer, LNT, DPF and SCR. The fuel reformer, LNT and DPF are positioned under the cab next to the fuel tank while the SCR is position in the vertical stack.

Figure 11 shows the detail components of the aftertreatment system. The right hand portion of the figure represents the exhaust inlet to the aftertreatment system. The exhaust enters the fuel reformer catalyst (11.81" OD x 3.99" long) through an expansion cone. A thermal mass that has equivalent size as the fuel reformer is positioned downstream of the fuel reformer to thermally isolate the LNT from temperature spikes. A 12" OD x 6" long LNT is used to adsorb the engine out NOx. The 12" OD x 12" long DPF is used to capture soot from the engine. The last catalyst is the SCR having a size of 12" OD x 6" long.

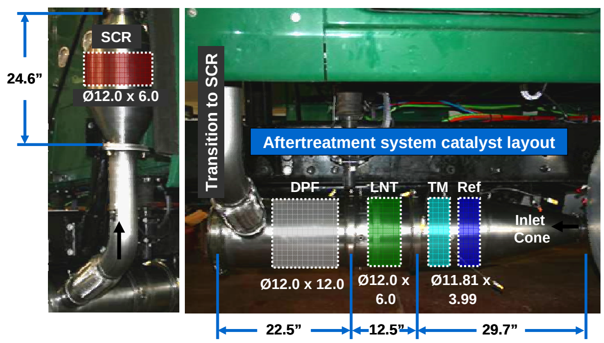

Figure 11. Aftertreatment Vehicle Setup

The aftertreatment system required a fuel injector having a flow range of 50 to 1000 grams per minute. Although this fuel system was developed, the vehicle demonstration used two fuel injectors each having a flow range of 30 to 500 g/min. Hence, a flow range of 30 to 1000 g/min was realized.

The aftertreatment emission and fuel usage results for a 13-mode dynamometer test cycle is summarized in Table 2 using slightly larger LNT and SCR catalysts than the catalysts used on the vehicle (12" OD x 8" long each). Key steady state operating modes were evaluated along with 13-mode test results. Engine out NOx was reduced from a range of 0.60 to 1.14 g/hp-hr down to a tailpipe level having a range of 0.09 to 0.25 g/hp-hr NOx. The EPA emission standards for NOx is 0.20 g/hp-hr having a not-to-exceed limit of 0.30 g/hp-hr. As a result, emission levels are met for all operating modes investigated. A 13-mode test was evaluated where the average engine out NOx was reduced from 0.61 g/hp-hr to a tailpipe level of 0.18 g/hp-hr. The average fuel usage for the 13-mode cycle was 1.5%. The dynamometer test results showed the ability to meet emission requirements while having a small impact on aftertreatment fuel usage.

Table 2. Aftertreatment Dynamometer Results

Operating Cycle	Engine BSNOx (g/hp-hr)	Tailpipe BSNOx (g/hp-hr)	Fuel Usage, %
13 Mode	0.61	0.18	1.50

The aftertreatment system that was tested on the vehicle had a lower engine out NOx calibration than the engine calibration used for the values shown in Table 2. The vehicle test used smaller LNT and SCR catalysts than the test cell (12" OD x 6" long). A comparison of aftertreatment fuel usage is reported in Table 3. The vehicle operated commonly at the A90 condition (i.e., low speed at 90% load). The average fuel usage was 1.30% at this operating mode. For comparison, the same size aftertreatment system was tested in the dynamometer cell. Since A90 was not tested, the surrounding operating modes are reported, A75 and A100. The fuel usage for A75 was 1.13% while the fuel usage at A100 was 1.46%. The A90 fuel usage is in line with the dynamometer fuel usage test results.

Table 3. Aftertreatment Vehicle Test Results

Test Venue	Operating Mode	Fuel Usage, %
Vehicle	A90	1.30
Dyno Test Cell	A75	1.13
Dyno Test Cell	A100	1.46

Figure 12 shows a typical DPF regeneration using the aftertreatment system described in the paper. The tailpipe fuel injection for this heavy duty engine required approximately 100 grams per minute fuel flow to clean the DPF. The fuel injection system operated at 4.8 bar during the DPF regeneration. The relative flow resistance (RFR) is indicative of the amount of soot on the DPF [6, 7]. The RFR decreased from 700 to 200 indicating that soot was removed from the DPF. The majority of the cleaning took place in the first 400 seconds as represented by the RFR decrease to 300. The test was run to 1000 seconds to show the relative decrease in RFR for this longer duration; thus, reducing the RFR to 200. Other parameters such as the turbocharger outlet pressure and pressure drop across the DPF show consistent trends with the RFR.

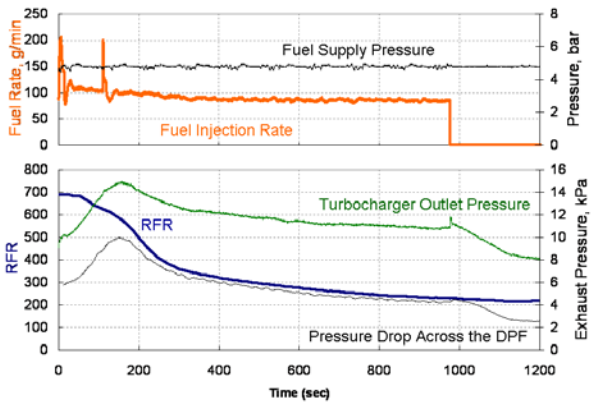

Figure 12. DPF Regeneration

The fuel injection system is appropriate for other aftertreatment markets including interim Tier 4 where diesel particulate reduction is the primary aftertreatment need. The fuel injection system provides a precise flow for systems with a fuel reformer that require operation in both lean and rich modes. Particulate treatment using DPF's operate only in lean mode. The small drop size distribution compared to other fuel injection systems [13] is appropriate for the DPF application since the fuel vaporization is proportional to the drop size. As a result, the mixing and vaporization system can be reduced in length using the proposed fuel injection system due to the small drop size distribution. This provides an opportunity to reduce the aftertreatment packaging profile.

Conclusions

An exhaust tailpipe fuel injection was developed for exhaust aftertreatment systems. A 30 to 500 g/min fuel injection system having average drop size characteristics between 55 and 70 microns (Sauter mean diameter) was developed and demonstrated on a fuel reformer, LNT, DPF and SCR aftertreatment system. The fuel injection system had a tight drop size distribution such that 90% of the spray volume had a drop diameter below 130 microns. Two fuel injectors were used for an aftertreatment demonstration on a heavy duty diesel engine platform. These fuel injectors each produced a fuel flow range of 30 to 500 g/min at 4.8 bar injection pressure such that the combined fuel flow ranged from 30 to 1000 g/min. These fuel injectors coupled with the aftertreatment system met the EPA NOx targets having a fuel usage of approximately 1.5%. The fuel injection system is appropriate for both NOx aftertreatment and DPF aftertreatment.

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