

Diesel Exhaust Aftertreatment System Packaging and Flow Optimization on a Heavy-Duty Diesel Engine Powered Vehicle

2010-01-1944

Published
10/05/2010

Philip Wetzel and James Edward McCarthy, Jr.
Eaton Corp.

Milind Kulkarni and Lokanath Mohanta
Eaton Technologies Private Limited

Gregory Griffin
Navistar, Inc.

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ABSTRACT

Diesel exhaust aftertreatment systems are required for meeting both EPA 2010 and final Tier 4 emission regulations while meeting the stringent packaging constraints of the vehicle. The aftertreatment system for this study consists of a fuel dosing system, mixing elements, fuel reformer, lean NOx trap (LNT), diesel particulate filter (DPF), and a selective catalytic reduction (SCR) catalyst. The fuel reformer is used 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 paper addresses system packaging and exhaust flow optimization for heavy-duty line-haul and severe service applications. Various packaging options are provided for both applications. Exhaust flow and fuel vaporization optimization was conducted using computational fluid dynamics followed by test cell and vehicle test results. Performance metrics were met including 97% uniformity for fuel vaporization and 97% uniformity for exhaust flow distribution having less than 2% fuel pulse broadening. The optimized system met the packaging constraints and EPA 2010 emission regulations.

I. INTRODUCTION

The Environmental Protection Agency (EPA) issued emission legislation for diesel engine vehicles. EPA year 2010 emissions are currently required for on-highway vehicles while meeting final Tier 4 emission standards for off-highway vehicles will be required in 2014. The feasibility of a fuel reformer, lean NOx trap (LNT) and selective catalytic reduction (SCR) aftertreatment system to meet a final Tier 4 emissions standard of 0.4 g/kW-hr NOx and EPA 2010 emission standards of 0.2 g/bhp-hr NOx has been addressed [1, 2]. This paper addresses the simulation optimization and vehicle packaging of an aftertreatment system meeting EPA 2010 emission regulations on a heavy-duty engine platform. Detailed simulation results are provided for vaporizing and mixing diesel fuel upstream of a fuel reformer catalyst. Multiple packaging options are provided using the simulation results for heavy-duty vehicle installations.

The aftertreatment system consists of a fuel dosing system, mixing elements, fuel reformer, LNT, diesel particulate filter (DPF), and 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) using 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 NO_x 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, 5,6,7,8,9]. The DPF is regenerated using the fuel reformer similar to a diesel oxidation catalyst by injecting fuel under lean exhaust operating conditions.

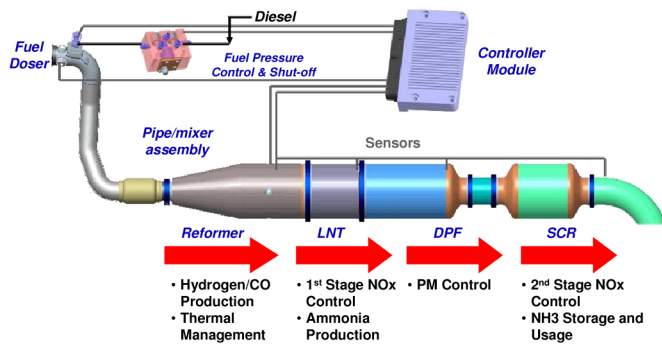


Figure 1. Aftertreatment system layout

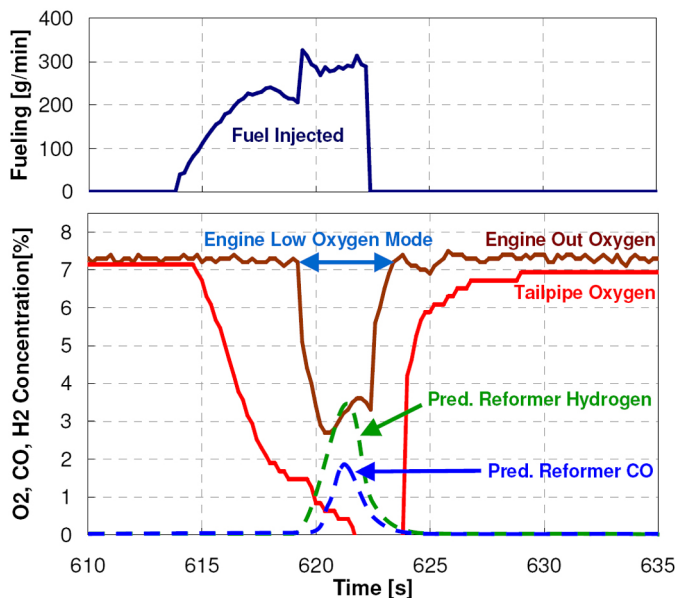


Figure 2. Typical reformer operation [1]

The fuel reformer is operated in both lean and rich modes to provide a means to regenerate the LNT and DPF in the aftertreatment system. Its two main functions during regenerations are 1) to consume the residual oxygen in the exhaust gas stream, and 2) to convert remaining fuel to the reductants, H_2 and CO [1, 5,6,7,8,9,10,11]. A typical reformer control is shown in Figure 2. Fuel is injected into the reformer to warm the catalyst to its operating temperature. Engine out oxygen is then reduced via engine control to a

lower level (i.e., 3.2% in the example). 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, as depicted by the predicted CO and H_2 profiles. The reformate is key to regenerating and desulfating the downstream LNT.

The fuel reformer operation is optimized by creating a uniform fuel and exhaust flow distribution upstream of the fuel reformer catalyst. Previous works have shown that the fuel distribution upstream of the fuel reformer is proportional to the downstream temperature distribution when the fuel reformer is operated in lean mode [12]. The fuel distribution is key during transitions from lean to rich mode operation. A uniform fuel distribution produces a uniform downstream temperature profile, while a non-uniform fuel distribution can result in non-uniform richness levels exiting the reformer. This paper will define key a metric for the fuel distribution that will be referred to as epsilon (ϵ). Likewise, the exhaust flow distribution metric referred to as gamma (γ) and the fuel pulse broadening metric referred to as psi (ψ) will be defined. The simulation results will be provided that meet the required targets for efficient operation of the fuel reformer.

The simulation optimization and packaging developed in this work were used to demonstrate heavy-duty aftertreatment emissions that met EPA 2010 levels. The fuel dosing system used in this work provides a smaller drop size distribution than previous works [12] and is described in recent literature [13]. The aftertreatment results from this work were applied to meeting EPA 2010 levels and were also described in recent literature [14]. The simulation results were applied to a 13L heavy-duty diesel engine. The engine was a 2010 development engine rated at 475 hp with peak torque of 1750 ft-lb. The engine was calibrated for two separate engine NO_x levels. As a result, two different aftertreatment systems were procured for the demonstration of meeting EPA 2010 tailpipe emission levels of 0.2 g/bhp-hr NO_x . The first aftertreatment system was sized for an engine out NO_x level of 1.0 g/bhp-hr while the second aftertreatment system was sized for an engine out NO_x level of 0.5 g/bhp-hr. Although two different aftertreatment systems were procured, the fuel injection system, fuel vaporization and fuel reformer catalysts remained the same for both systems. As a result, the fuel vaporization simulation applied to both aftertreatment systems.

II. EXPERIMENTAL SET-UP

SYSTEM PACKAGING

Figure 3 shows a ProStar vehicle that was used for the aftertreatment demonstration which includes the aftertreatment system. 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 3. Aftertreatment demonstration vehicle

The aftertreatment system was sized for two separate engine calibrations. Table 1 shows the sizing for an engine NOx calibration of 1.0 g/bhp-hr and 0.5 g/bhp-hr. Two systems were sized to meet the EPA 2010 emission NOx level of 0.2 g/bhp-hr. The fuel reformer was sized to 300 mm (11.81") OD $\times$ 101.5 mm (3.99") long for both engine calibrations. A thermal mass that had equivalent size as the fuel reformer was positioned downstream of the fuel reformer to thermally isolate the LNT from temperature spikes. A 304.8 mm (12") OD $\times$ 203.2 mm (8") long LNT was used to adsorb the engine out NOx on the high NOx engine while a shorter LNT (i.e., 152.4 mm (6") long) was used on the low NOx engine. The 304.8 mm (12") OD $\times$ 304.8 mm (12") long DPF was used to capture soot from the engine. The last catalyst was the SCR having a size of 304.8 mm (12") OD $\times$ 203.2 (8") long for the high NOx engine and a shortened SCR (i.e., 152.4 mm (6") long) for the low NOx engine.

Table 1. Sizing of the Aftertreatment System Components

System	Engine out NOx [g/bhp-hr]	Sizing (inches)	Reformer	Thermal Mass	LNT	DPF	SCR
High NOx	~ 1.0	Diameter	11.81	11.81	12	12	12
		Length	3.99	3.99	8	12	8
Low NOx	~ 0.5	Diameter	11.81	11.81	12	12	12
		Length	3.99	3.99	6	12	6

Figure 4 shows the experimental system layout used for the aftertreatment system evaluation. The system consists of (a) an in-line fuel doser, (b) downpipe with a mixer, (c) fuel reformer, (d) thermal mass upstream of (e) LNT, (f) DPF, and (g) SCR. This packaging layout was installed on the ProStar vehicle. The main focus of this paper was developing the proper mixing and vaporization system from the fuel doser to the fuel reformer. The vehicle routing of the downpipe was fixed while the mixing elements and the inlet cone to the fuel reformer were key elements optimized using computational fluid dynamics (CFD). The vehicle packaging was developed

using aftertreatment fuel injection and vaporization simulations [12].

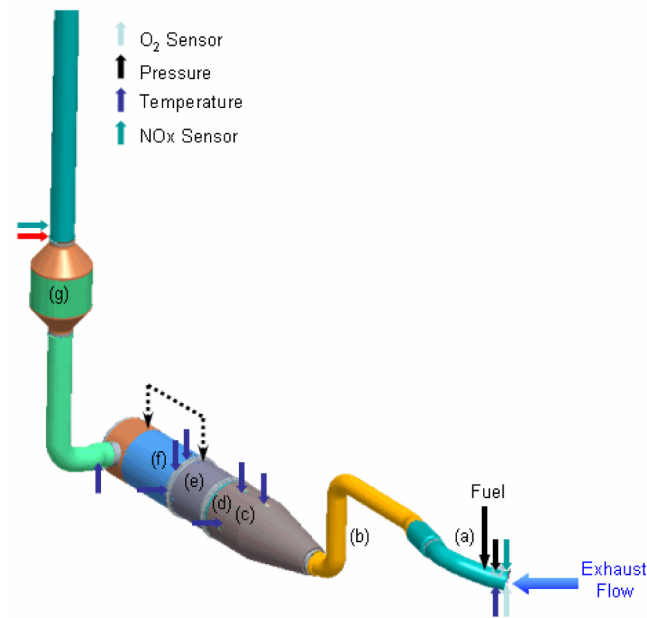


Figure 4. Experimental system layout

Figure 5 shows the installation of the aftertreatment system on the ProStar vehicle. The aftertreatment system included dual fuel injectors for in-pipe diesel injection, a custom downpipe, removable DPF cap for ash cleaning, an electronic control unit (ECU) for aftertreatment controls, and a wiring harness. The right hand portion of the figure represents the exhaust inlet to the aftertreatment system. The exhaust entered the fuel reformer catalyst through an expansion cone. The thermal mass, LNT, DPF and SCR were positioned downstream of the fuel reformer. The vehicle was operated with the low NOx engine calibration. The heavy-duty vehicle was fitted with provisions for aftertreatment systems using both the high and low NOx engine calibrations as the main difference was the length of the LNT and SCR catalysts. The length of the LNT and SCR canning was set for the longer catalyst bricks while for the low NOx calibration, shorter bricks were installed.

The aftertreatment system required a fuel doser having a flow range of 50 to 1000 grams per minute to meet the heavy-duty aftertreatment fuel flow requirements for all modes of operation. Although a fuel system was developed having this flow rate, the aftertreatment demonstration vehicle 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 fuel dosers were mounted to the exhaust pipe on the vehicle as shown in Figure 6. The fuel dosing system had a drop size distribution that was conducive for fuel vaporization having a Sauter mean diameter ranging between 60 and 70 microns [13]. These drop sizes are smaller than previous fuel dosing

systems [12]. The fuel injectors employed a recirculating cooling loop from the fuel tank to an external electrical pump, which funneled diesel fuel to the injectors and back to the fuel tank. The fuel would be supplied from the low pressure gear pump for serial production.

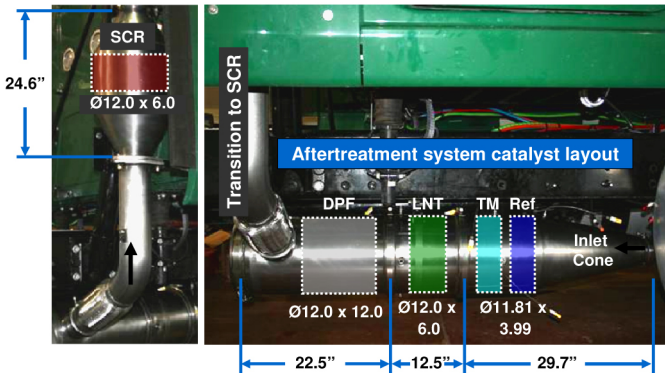


Figure 5. Aftertreatment vehicle setup



Figure 6. Aftertreatment fuel dosing system mounted to the vehicle exhaust pipe

The aftertreatment system test results from the simulations described in this paper are cited in the literature [14]. The test results include both dynamometer and vehicle test results for the required test cycles showing compliance to EPA 2010 emission standards.

CFD METHODOLOGY

The design process for developing the fuel vaporization and mixing upstream of the fuel reformer catalyst relied on CFD simulations prior to procuring hardware. Previous works showed that hardware iterations can be reduced using fuel vaporization and mixing models [12]. Multiple design iterations can be tested in a short period of time by relying on computer simulation to predict flow dynamics.

This section provides a description of the key CFD steps used to develop the fuel vaporization and mixing in the

aftertreatment system downpipe. A general description of the engine operating conditions and its affect of fuel vaporization is provided. The effect of exhaust temperature and mass flow rate on fuel vaporization and mixing is described. The key engine operating conditions used for CFD are described followed by a description of the exhaust flow uniformity (γ), fuel vapor uniformity (ϵ) and fuel pulse broadening (ψ). These steps were followed to optimize the exhaust downpipe prior to procuring hardware for testing.

Identifying the proper engine operating conditions for simulation is necessary for the design process of each new application. The most challenging exhaust gas temperature and mass flow rate conditions for vaporizing and mixing hydrocarbons injected into the exhaust pipe need to be selected to limit the amount of simulation time while ensuring proper system performance. Liquid hydrocarbons are injected into the exhaust pipe. These liquid hydrocarbons must be vaporized and thoroughly mixed to create a uniform exhaust gas/hydrocarbon vapor mixture at the inlet to the fuel reforming catalyst to ensure proper operation [12]. The hot exhaust gas is the only source of heat to vaporize the injected hydrocarbons; therefore exhaust gas temperature plays a critical role in hydrocarbon vaporization. Exhaust gas mass flow rate has a large effect on mechanical mixing. Finally, engine duty cycle needs to be considered to ensure proper system operation under the engine conditions most often encountered with a given application. Higher power engine conditions require larger amounts of hydrocarbons to be injected into the exhaust stream than lower power conditions. Engine duty cycle, exhaust gas temperatures, and exhaust gas flow rates are all considered when choosing the engine conditions to simulate with CFD.

Exhaust gas temperature is important to the vaporization of the injected hydrocarbons. The heat produced by the engine is the primary means to vaporize the injected hydrocarbons. A temperature threshold exists above which the exhaust gas temperature is needed for the reforming catalyst to operate, also known as light off. Exhaust gas temperatures below the light off temperature of the reforming catalyst are not conducive to operation of the reforming catalyst; thus, hydrocarbon injection is avoided at these low temperatures. The reforming catalyst light off temperature serves as the lowest possible temperature for which hydrocarbons will need to be injected and vaporized.

Exhaust gas mass flow rate is also an important parameter that was evaluated during the CFD design process. Diesel engines in commercial vehicles operate in a combination of steady state and transient performance. Line-haul vehicles spend a majority of their time operating in steady state conditions while severe service vehicles such as refuse vehicles operate in a stop-and-go environment. The aftertreatment system must be designed to perform well across a wide range of exhaust mass flow conditions. Low