

Fuel Injector Optimization for Diesel Aftertreatment Systems Coupled with Exhaust Aftertreatment System Performance on a Heavy-Duty Diesel Engine Powered Vehicle

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ABSTRACT

Exhaust system fuel injection is required for many diesel engine aftertreatment systems including diesel particulate filter (DPF) systems, fuel reforming systems and lean NO_x trap (LNT) systems. The design objective of this work was to develop exhaust system fuel injectors 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 fuel reformer, LNT, DPF and selective catalytic reduction (SCR) catalysts. Three system fuel injectors with high turndown ratios (16.5:1 to 25:1) were developed to provide fuel flow ranges of 10 to 250 grams per minute, 30 to 500 grams per minute and 50 to 1000 grams per minute. The fuel sprays consisted of droplet Sauter mean diameters (SMD) that ranged between 55 to 70 μm within a fuel supply pressure that ranged between 4.8 and 7.0 bar. A higher pressure of 8.3 bar was used for the highest flow injector resulting in a SMD range of 60 to 75 μm . The medium flow injector (30 to 500 grams per minute) was demonstrated on an aftertreatment system that was sized to meet EPA 2010 emission standards for an on-highway heavy-duty diesel engine. The 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 active DPF regeneration. During rich mode operation, diesel fuel was converted to hydrogen and carbon monoxide in the fuel reformer for LNT regeneration and desulfation. 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.

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 NO_x trap (LNT) and selective catalytic reduction (SCR) aftertreatment system to meet a final Tier 4 emissions standard of 0.4 g/kW-hr NO_x and EPA 2010 emissions standard of 0.2 g/bhp-hr has been addressed [1, 2]. The 0.4 g/kW-hr NO_x standard is applicable for engines having rated power levels above 56 kW. This paper addresses the development and demonstration of a fuel doser in both a NO_x and particulate aftertreatment system.

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 (H₂) and carbon monoxide (CO) using injected diesel fuel. These reductants are used to regenerate and desulfate the LNT catalyst. NO_x emissions are reduced using the combination of the LNT and SCR catalysts. During LNT regeneration, ammonia (NH₃) 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 system has competitive fluid consumption costs when compared to a urea-SCR system that requires both diesel fuel and urea solution. The DPF is regenerated using the fuel reformer similar to diesel oxidation catalyst by injecting fuel under lean exhaust operating conditions.

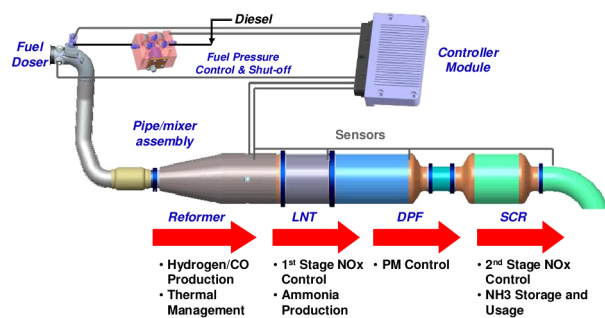


Figure 1. The aftertreatment system layout includes the fuel dosing system, mixing elements, fuel reformer, lean NOx trap, diesel particulate filter and selective catalytic reduction catalysts.

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 NOx 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. The operation of the reformer is cited in literature [1, 5, 6, 7, 8, 9, 10, 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 (i.e., 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 reformat is produced, depicted by the predicted CO and H_2 profiles. The reformat is key to regenerate and desulfate the downstream LNT.

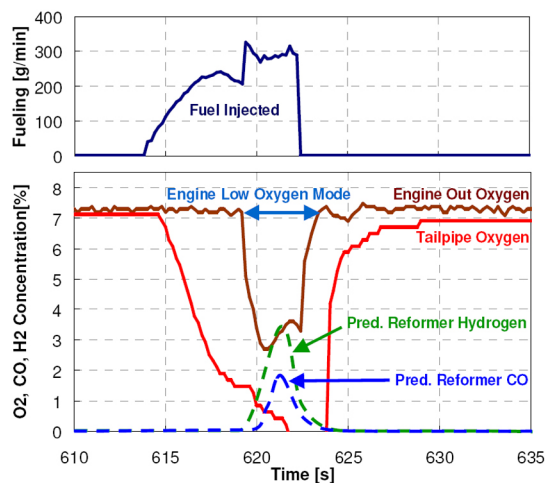


Figure 2. Typical reformer operation [1].

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-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 with a pintle that acts as an internal shutoff. The pintle is actuated 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 and pressure ranges. Flow ranges include 10 to 250 g/min, 30 to 500 g/min, and 50 to 1000 g/min. Flow rates up to 500 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 8.3 bar.

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 at

the top of the injector. 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 between 5% and 95% duty cycle. These duty cycles correspond to the minimum and maximum flow rates for each injector.

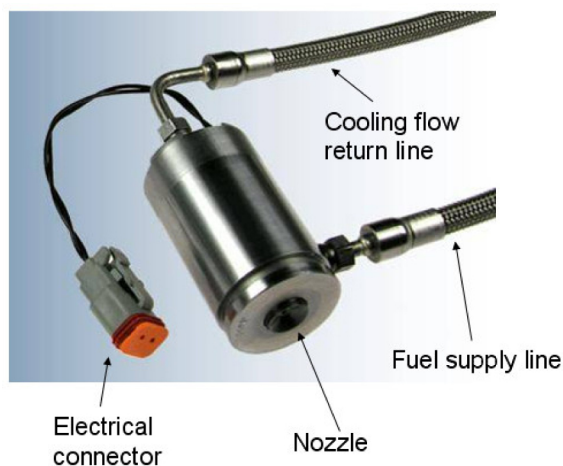


Figure 3. The fuel injector is shown. Voltage is applied to the electrical connector to open the injector. Fuel provided by the fuel supply line exits from the nozzle. Cooling flow carries away heat as it exits through the return line.

The fuel injector can be mounted directly to an exhaust pipe since the nozzle is continuously cooled with fuel. Figure 4 shows a sample installation on the vehicle where two fuel dosers are mounted directly to the exhaust pipe. A simpler installation is being developed that does not require a welded boss to the exhaust pipe. The exhaust pipe will be formed with localized flat portions where the fuel doser can be directly mounted to the pipe eliminating any special bosses or heat shields.

A model of the FMA is shown in Figure 5. 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 (A), an optional “spin on” 20-micron fuel filter (B), a two-way normally closed proportional flow control valve (C), a special two-way normally closed (N.C.) fuel cutoff valve (D), a pressure sensor (E), check valve (F), and four manifold fittings (G-J) for the various mating fuel hose connections. The optional fuel filter is used in applications where existing pump filtration exceeds the validated 20-micron limit for the FMA and injector. As the contamination constituents can vary from application to application, reliability needs to be assessed under a customer's specific operating conditions. The manifold block footprint is approx. 118mm × 118mm × 45mm while other footprints have been customized. While

the assembly used in evaluation testing was configured for vehicle chassis frame rail mounting, other mounting configurations such as the engine are possible and require additional verification testing with respect to vibration.

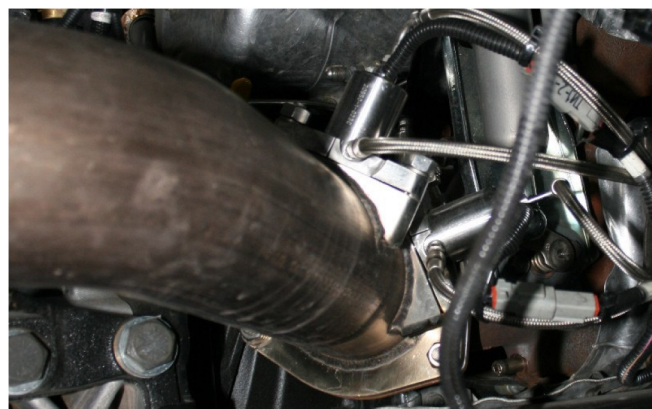


Figure 4. Aftertreatment Fuel Dosing System Mounted to the Vehicle Exhaust Pipe [12].

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 primary functions:

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

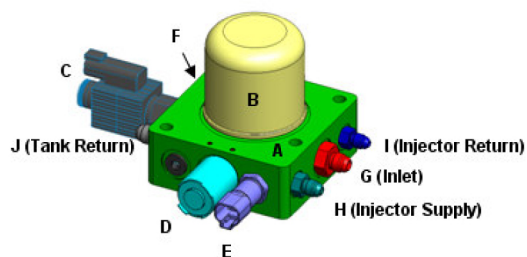


Figure 5. The fuel manifold assembly including (A) a fuel distribution block, (B) fuel filter, (C) a two-way flow control valve, (D) fuel cutoff valve, (E) a pressure sensor, (F) a check valve, and (G-J) manifold fittings.

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

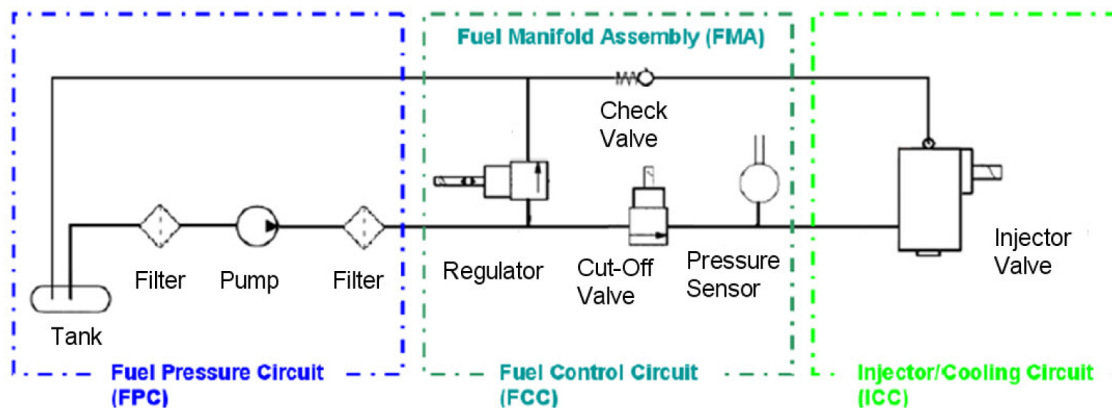


Figure 6. The schematic of the FMA shows the fuel pressure circuit, the fuel control circuit and the injection cooling circuit.

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 the FMA to shutoff fuel flow to the dosing fuel injector in the event that fuel leakage occurs.

FUEL INJECTION SYSTEM DEVELOPMENT - FUEL SYSTEM ASSEMBLY (FSA)

The Fuel System Assembly (FSA) schematic in [Figure 6](#) depicts the three fuel circuits used to support fuel injection within the engine exhaust aftertreatment system including the Fuel Pressure Circuit (FPC), the Fuel Control Circuit (FCC) and the ICC.

The FPC is responsible for the filtered flow delivery and return of diesel fuel. It functions to provide fuel flow to and from the fuel tank and FMA via fuel supply and return lines. Due to cost considerations, this circuit is usually part of the low pressure pump circuit on a diesel engine. An auxiliary electric fuel pump can be used for higher fuel flow dosing applications where additional pump capacity is required.

The FCC consists of the FMA which provides fuel pressure regulation at 4.8 bar $\pm$ 0.2 bar to the injector for injection and injector cooling. The FMA also supports additional operating functions such as fuel leak detection and fuel shut-off capability within the ICC. Although pressure regulation and leak detection functions are available on the FMA, elimination of these features is possible to allow for smaller packaging and efficiency. In an application utilizing an existing low pressure gear pump, it may be possible to use the existing regulated pressure output that would supply the FMA.

Various levels of pressure regulation and leak detection are available and are dependent on application needs. Depending on flow accuracy requirements, it is possible to manage

injector flow delivery without secondary pressure regulation. This is accomplished using a three-dimensional injector characterization algorithm that produces the necessary command flow rate as a function of injector duty cycle and supply pressure. A set of coefficients is bar coded on each injector during production end-of-line testing. These coefficients are read by the customer and flashed into vehicle electronic control unit (ECU) memory as additional control logic to achieve higher flow as a function of duty cycle accuracy.

The ICC is comprised of the fuel injector and injector supply/return lines. The injector supply line delivers pressurized fuel from the FMA to the injector. The injector return line provides a path for injector fuel spill/cooling flow from the injector to the FMA. Return fuel is then delivered back to the fuel tank for reuse. [Figure 7](#) illustrates the components used in FSA testing and is representative of what is used for prototype evaluations.

[Figure 8](#) depicts the fuel flow through the FMA during normal operation. A proportional flow control valve within the FMA, provides the pressure control capability to regulate fuel pressure to the injector. Fuel pressure is maintained at 4.8 bar $\pm$ 0.2 bar under closed-loop control using the output pressure signal feedback from the manifold pressure sensor. This type of pressure control strategy serves to minimize the commanded versus actual fuel flow rate error that results due to supply pressure variations caused by changes in injector flow demand. It also enables the fuel system to run at different supply pressures to achieve higher injector fuel turndown ratios and better spray quality, if required. Turndown ratio is defined as the ratio of the maximum to minimum flow rate. The fuel cutoff valve must be energized during engine operation in order to regulate supply pressure to the injector. This action also ensures adequate cooling flow to the injector to prevent it from overheating and causing possible damage.



Figure 7. FSA components; auxiliary fuel pump housing, fuel manifold assembly, injector, and associated fuel lines.

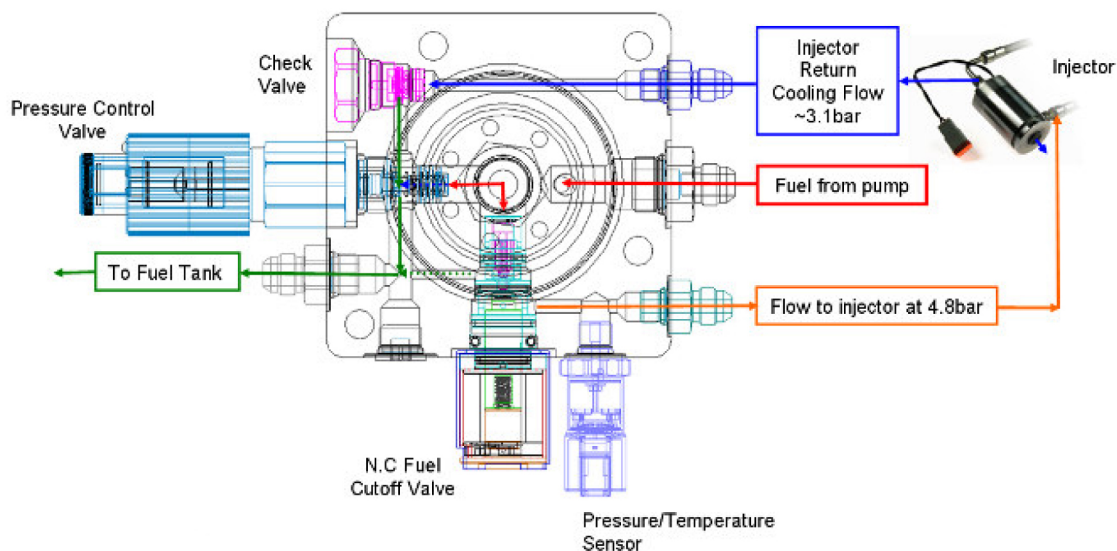


Figure 8. FMA Normal Operating Function - Fuel Cutoff Energized.

Figure 9 depicts the state of holding pressure during leak detection. A leak detection event normally proceeds after the end of a fuel injection cycle. The injector is de-energized to the closed position when a leak check is initiated. This action should stop the flow of fuel into the vehicle exhaust stream. The fuel cutoff valve is then de-energized to its normally closed position. The special design of this valve allows for the unloading of supply pressure from the valve poppet in the normally closed position. This ensures that pressurized fuel cannot enter into the ICC and bias the leak down measurement. Pressure in the ICC quickly decays to the reseating pressure of the check valve 3.1 bar. The signal output from the pressure sensor is then monitored over a ~3 sec. test period. Leakage is deemed to be within acceptable

limits if the pressure is above a certain threshold over the specified time period. The leak rate is deemed to be out of specification if pressure falls below the threshold limit.

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 turndown ratio greater than 15:1, using a supply pressure that can be produced by typical low pressure gear pumps available on diesel engines. Both high and low flow rates are required by the fuel reformer, LNT and DPF systems at fuel supply pressures on the order of 4.8 bar.

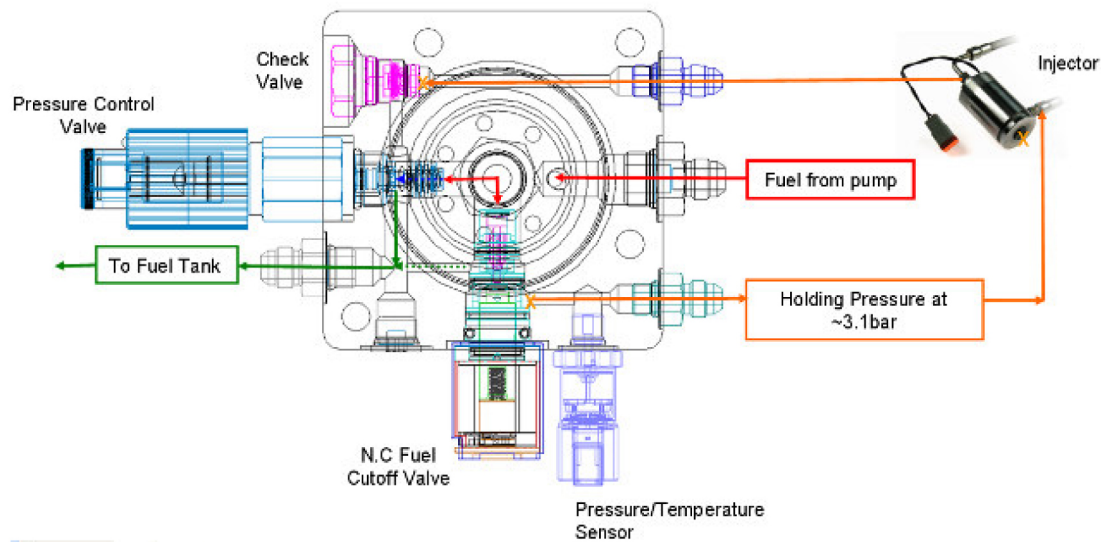


Figure 9. FMA Leak Detection Function - Fuel Cutoff De-Energized.

A pressure swirl atomizer was selected to meet the design goals. This design strategy allows for a system that can be adjusted to achieve multiple flow range targets with minimal geometry changes.

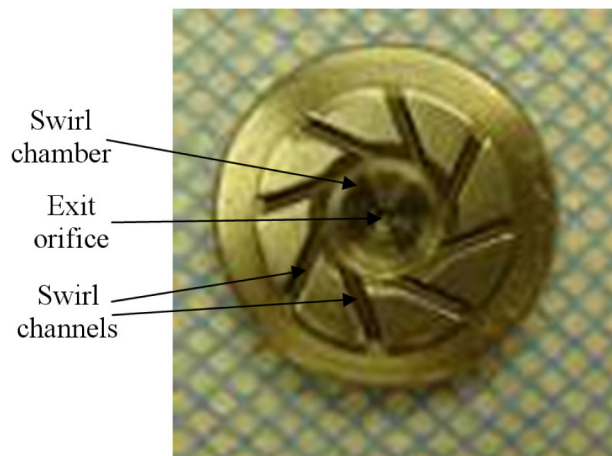


Figure 10. Injector Nozzle Geometry.

Figure 10 shows the internal geometry of the nozzle of a pressure swirl atomizer. 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 tangential velocity as it moves towards the exit orifice. The fluid swirls fast enough to create centrifugal forces that lead to a low pressure zone along the axis of the chamber and in the center of the exit orifice. Exhaust gas enters the injector through the fuel exit orifice and forms an air core along the axis and in the center of the orifice. The exiting fuel forms a thin circular

sheet surrounding the air core. Aerodynamic forces break the fluid sheet into drops after it exits the injector. The desired atomization qualities for a given flow rate are achieved by adjusting the geometry of the swirl channels, exit orifice and swirl chamber to control the size of the air core.

The geometry of the pressure swirl atomizer was sized by creating a simple physics model. An inviscid model was used such that viscous and fluid shear forces were disregarded. A unique air core size and total flow rate can be calculated from the model for a given exit orifice size, swirl channel size and channel entry radius. The model included the following assumptions:

1. The average fluid velocity in the channels is equal to the total injector flow rate divided by the total cross sectional area of the channels.
2. Angular momentum is conserved. The angular momentum as the fluid exits the swirl channel is equal to the angular momentum at the boundary of the air core for a given mass of fluid.
3. The velocity in the axial direction of the exiting fluid is equal to the total injector flow rate divided by the difference between the area of the exit orifice and the area of the air core.
4. Any loss of potential energy in the fluid corresponds to a gain in an equivalent amount of kinetic energy in line with Bernoulli's equation for conservation of energy in fluids.
5. Fuel consumption is maximized. Among all possible flow rates and air core sizes, the swirling fluid will move towards a steady state that maximizes the total injector flow.

These assumptions can be expressed mathematically as:

