

Development of Common Rail and Manifold Fluid Delivery Systems for Large Diesel Engine Aftertreatment

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ABSTRACT

EPA 2015 Tier IV emission requirements pose significant challenges to large diesel engine aftertreatment system (EAS) development aimed at reducing exhaust emissions such as NO_x and PM. An EAS has three primary subsystems, Aftertreatment hardware, controls and fluid delivery. Fluid delivery is the subsystem which supplies urea into exhaust stream to allow SCR catalytic reaction and/or periodic DOC diesel dosing to elevate exhaust temperatures for diesel particulate filter (DPF) soot regeneration. The purpose of this paper is to discuss various aspects of fluid delivery system development from flow and pressure perspective. It starts by giving an overview of the system requirements and outlining theoretical background; then discusses overall design considerations, injector and pump selection criteria, and three main injector layouts. Steady state system performance was studied for manifold layout. The transient pressure fluctuations from injector activations and deactivations were measured by using both pressure gauges and high frequency sampling devices. It is observed that a low pressure common rail demonstrates high level of pressure fluctuations; therefore countermeasures such as hardware changes and control software options were implemented. Along with measurements, CFD models and flow network models were developed and compared to test data. The discrepancy between tests and modeling were analyzed and reviewed. Multiple designs of experiments by tests and modeling were carried out to study specific system performance and design parameters. Recommendations were provided with respect to reducing pressure fluctuations and maintaining stable steady state pressure.

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INTRODUCTION

Large diesel engines generate significant pollutants from internal combustion processes; they are NO_x, particulate matters (PM), unburned hydrocarbons (HC), and carbon dioxides (CO). To reduce these pollutants, urea SCR is the mainstream technology to reduce NO_x, while DOC / DPF / active regenerations are the main technology to reduce CO, HC and PM. These catalytic reactions require reagents such as urea and HC to be dosed in the hot exhaust gas to react with the gaseous species. Fluid delivery system, as a subcategory of the overall aftertreatment system, provides responsive and accurate reagent (HC or urea) dosing rates, low maintenance and cost, robust operations and compact packaging space.

The fluid delivery system development involves the integration of injectors, pumps, filters, regulators, tanks, pressure transducers and the necessary control mechanisms to achieve targeted fluid dosing within cost and packaging constraints. The system, in terms of fluid dynamics, can be represented mathematically by incompressible flow /

hydraulic network described by two main variables: pressure and flow rate. Intuitively, such system differs from typical diesel engine fluid delivery system in that the operating pressure (generally below 10 bar) is much lower than that in high-pressure common rail systems (up to 1000 bar) in diesel powertrain. Seemingly simple, however, such a low pressure fluid delivery system presents its own challenges. The first challenge comes from tradeoffs in the design of system layout which demands a balance between component complexity and control simplicity. The second challenge arises from injector dynamic behavior which, if not controlled properly, tends to magnify rather than dampen the pressure fluctuations.

The integrations of fluid delivery components for light, medium and heavy duty truck applications are rather simple in that they need only one dosing source per reagent, for example, one injector per urea or HC. In contrast, large diesel engines emit 10 times more emissions, dictating both larger diameter pipes as well as much higher dosing rates. Hence more system components, typically, 8 to 14 urea injectors and

6-10 HC injectors are required. Given such large number of injectors, proper design of the system layout is therefore an important step in system planning and development. In pressure control, the pros and cons of mechanical regulators versus dynamically controlled pump need to be well understood.

This paper first presents the challenges faced with developing fluid delivery systems; then proceed to analyze various specific factors relevant to system design, next three design options including single-path, manifold and common rails are discussed. Necessary simulation and test validations are provided. The development process and methodologies are discussed among these subjects.

OVERVIEW OF LARGE DIESEL AFTERTREATMENT SYSTEM

In large-scale diesel engines such as locomotives, marine vessels, and stationary generator applications, the aftertreatment system development generally dictates modularity, simplicity and manufacturability for the subsystems. The scalability and versatility of modular components have benefits of being cost-effective and maintenance friendly for many diverse systems. The system layouts may vary, but it must meet the comprehensive performance targets of back pressure, reductions of NO_x, PM, CO and HC, system durability, cost, and maintenance [1] [2]. For a typical locomotive, marine or stationary generator engine with 8 to 20 cylinders and 800 to 4590 BHP, the Particulate Matter (PM) reduction target could be over 90% and the NO_x reduction target over 65% for long running conditions with possibly severe emissions. The urea and HC consumption rates are typically at 10-60 kg/hr and 30-180 kg/hr depending on engine development strategy towards lower NO_x and higher PM or vice versa. Such flow rates can exceed capacity of single urea or HC injector. In addition, short mixing distances and large diameter pipe may drive a packaging solution of multiple injectors clocked around the circumference of the pipe to facilitate reagent penetration deep into the exhaust flow stream.

As reagents to reduce NO_x and oxidize PM, Urea or HC are supplied by a pump through filters and delivered to injectors, where pressurized liquid was released periodically into the exhaust stream. The pressure difference between injector and fluid exhaust gas is typically at 80-140 PSI in order to allow liquid to breakup into fine particles in the exhaust airstream. The dosing rates of these reagents depend on exhaust condition, desired reduction targets (for urea SCR), and desired active regeneration temperature conditions (for DOC dosing). In addition, DOC requires activation temperature (at 250 °C or higher) to allow DOC precious metal catalyst to be active and enable the oxygen to react with HC. SCR requires an activation temperature (180 °C or higher) to allow SCR catalyst to enable ammonia to react with NO_x and minimize deposit formations [2]. It is worth noting that Urea SCR dosing is typically done whenever the

exhaust temperature is above the 180 °C activation temperature while DOC dosing is only done periodically when soot accumulation in the DPF has risen to a threshold value. Also, the temperature window above may necessitate using a regeneration unit such as a burner to raise temperature to catalyst activation temperature. Therefore three external inputs are needed to make the chemical conversion processes possible. They are external heat, HC and urea. A schematic view of the system is shown in Figure 1 [3].

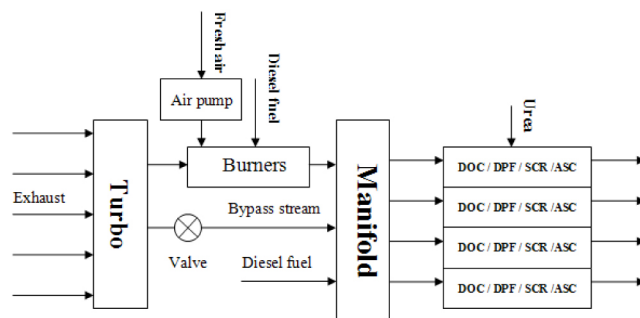


Figure 1. Schematics of fluid / heat inputs for large diesel engine aftertreatment system [3]

In the above schematics, the heat is supplied by an exhaust diesel burner to achieve DOC activation temperature and / or by a catalytic burner (DOC + HC dosing) to achieve DPF active regeneration. In large diesel engines, often times, the aftertreatment system is mounted close to the exhaust stack which are above the engine mount locations. In contrast, the reagent (urea or HC) tank is mounted below engines, requiring a fluid lift of 2-4 meters. These heights for large diesel engines pose more demand on the fluid delivery pump than does that of light vehicle or truck applications.

STEADY HC AND UREA CONSUMPTION RATES

Urea consumption rate is dependent on exhaust mass flow rate, NO_x concentration, catalyst coating and NO_x reduction target. The urea consumption rate can be written as:

$$m_u = m_s E_f F_{.u} \quad (\text{Eq. 1})$$

where m_s is theoretical urea flow rate to achieve full reduction of NO_x at stoichiometric ratio of 1, E_f is the target NO_x reduction rate, $F_{.u}$ is the magnification factor (typically more than 1) that accounts for ammonia wasted during urea transport from injector to SCR, such as urea deposits, ammonia oxidization, species (NO_x and NH₃) storage and etc.

The hydrocarbon consumption can be obtained according to catalyst exothermic reactions:

$$m_h = m_s(1-L)F_h = \frac{m_e C_p (T - T_e)}{Q_d} (1-L)F_h \quad (\text{Eq. 2})$$

Where m_s is the theoretical hydrocarbon dosing rate required to raise exhaust temperature from current temperature T_e to regeneration temperature T . In calculating m_s , m_e is the exhaust mass flow rate, C_p is the specific heat for exhaust gas, Q_d is the combustion heat for diesel fuel. L is the heat loss factor. The heat loss generally arises from heat loss to environment via radiation and convection mechanisms. Similar to F_u , F_h is the magnification factor (typically more than 1) that accounts for extra HC dosing to compensate HC wasted during transport process.

The actual urea and HC consumption rates m_u and m_h depend on exhaust species composition, catalyst loading, catalyst aging, ammonia / HC slip tolerance, and transients from engine. Engine dynamometer tests are necessary to derive the calibrated dosing rates, hence to determine F_u and F_h which are functions of engine load parameters and reagent mixing situation. The above formula could be extended to transient processes though the transient events introduce challenges to control algorithms with respect to how to time the delay of certain events such as active regenerations.

ESTIMATION OF PRESSURE DROPS IN FLUID DELIVERY SYSTEM

For most restriction-based fluid delivery components such as valve, regulators, and injectors, the relationship between the fluid flow rate and pressure drop can be described by incompressible orifice flow restriction formula:

$$m_f = CA\sqrt{2\rho\Delta P} \quad (\text{Eq. 3})$$

Where m_f is the fluid mass flow rate, C is the flow coefficient, A is pipe cross-sectional area, ρ is the density, ΔP is the pressure drop.

In large diesel systems, the fluid needs to reach at elevations up to 4-6 meters. The pressure distribution between different components can be roughly described by the following Bernoulli's formula:

$$\Delta P = \rho g \Delta Z + f \frac{\rho L V^2}{D} \quad (\text{Eq. 4})$$

Where ρ is density, g is the gravitational constant, L is pipe length, D is pipe diameter, and V is the average velocity of fluid. ΔZ is elevation and f is friction coefficient.

HIGH LEVEL DESIGN CONSIDERATIONS

An example is given here with respect to engine output conditions and reagent consumption needs. Assuming that a typical large engine has 2000 KW specific power, engine displacement volume 150 Liters, mass flow rate 15,000 kg/hr, exhaust temperature 300 C, and engine out NOx 6 (g/hp.hr), according to Eq. (1-2), the urea consumption rate m_u can be estimated as 24 kg/hr and the diesel fuel consumption rate m_h is 156 kg/hr for active regeneration.

Such high dosing rates indicate that a single injector is not enough to supply the fluid to the system needs, necessitating multiple injectors to supply fluids. The determination of the number of injectors depends on the overall mixing and distribution of such liquids as well. In modular aftertreatment design, the multiple modules or legs could determine the number of the injectors.

The following steps need to be followed in order to achieve proper design of fluid delivery system

- Select injector type and orifice sizes by confirming the flow range and spray characteristics, ensure that the injector satisfy the mixing needs with respect to average particle size, distribution and impingement velocity.
- Determine the number of injectors, during which care is taken to ensure that system dosing rates fall into linear injector operating performance curves for proper software control.
- Determine the system layout. Questions arise regarding to whether manifold concept or common rail concept should be adopted. The manifold concept allows for a single flow stream to be divided into 2-4 injectors per pump. The common rail system allows for a single supply pipe for 5-15 injectors from a single pump. The choice of system layout depends on packaging layout and system simplicity
- Select pump, filter, regulator according to flow rate requirement and transient run requirement.
- Validate the system via lab scale tests. Steady and transient pressure and flow rate should be monitored and compared across the system. Uniform flow distribution and stable pressure should be the key focus.
- Validate components for cooling and control strategy for operational tests under actual vehicle/ vessel conditions.

In any case, the system should be designed such that the pressure and flow should be sufficient for normal / stable operational conditions with temperature variations and mechanical vibration. The system should also be allowed to perform at contingent modes of operations that require the system be overdesigned with a safety margin over normal operations.

PUMP AND INJECTOR SELECTIONS BASED ON REAGENT CONSUMPTION RATES

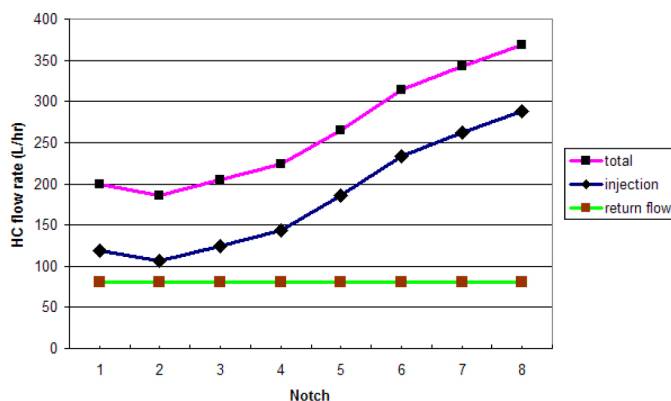


Figure 2. System HC consumption and cooling flow rates at different steady state notch conditions for a large locomotive engine.

Once the engine emission data are known, the overall system consumption rates can be calculated based on Eq. (1-2). Figure 2 gives typical hydrocarbon consumption rates at different steady state conditions for the whole system. With assumption of 8 injectors and cooling flow rate of 10 L/h per injector, the total system cooling rate can be estimated at 80 L/h, a constant across all conditions. The urea consumption rates can be obtained in similar way. Note the cooling rate is partially determined according to the tolerance of injector thermal stress at the worst case scenario of DPF active regeneration temperature.

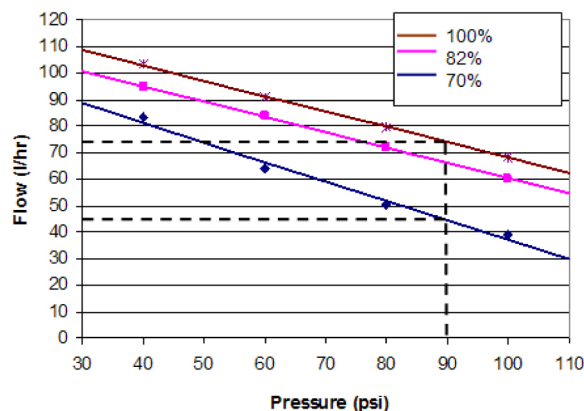


Figure 3. Flow-pressure characteristics for a urea pump at three points of percentage on time (duty cycle).

Injector and pump flow characteristics should be determined at various points of percentage on time in order to estimate whether they can meet system consumption at the targeted run conditions. An example is given in Figure 3, where the urea pump delivers increasing flow rates with

pump percentage on time (proportional to pump power output). At pump inlet pressure of 90 PSI, the pump can deliver 72 L/h at rated (100%) power and 46 L/h at 70% power under steady state operation. It is recommended to run pumps at certain percentage on time, beyond which the pump may have long-term durability issues.

Injector flow characteristics can be determined as well. Injector flow rates should cover the range of reagent (Urea and HC) consumption rate with some safety factor. For the ease of injector control, the injector dosing rate should be at the linear curve between flow rate and percentage on time.

With larger flow rate requirements, system components from medium and heavy duty truck applications may either be upgraded to a multiple injectors multiple pump system or for reduced complexity a single pump multiple injector system. For example, the pump needs to possess higher flow capability with excellent durability. The selection and sourcing of fluid delivery components therefore are critical steps of system development.

Given constrained pump capacity, the injector may need to be redesigned with lower flow rate. Since the total flow rate incorporates both dosing flow rate and cooling flow rate, one way is to reduce the injector cooling flow rate. In this study, the injectors for common rail have been redesigned with 10 L/h cooling flow rate from a higher liter per hour flow rate. It is worth noting that lower cooling flow rate must be able to sustain the life of injector in the high temperature environment.

SINGLE-PATH BASED FLUID DELIVERY SYSTEM

The intuitive way of designing fluid delivery system is to allow the flow to go through a sequential path from tank to injector, as shown in Figure 4.

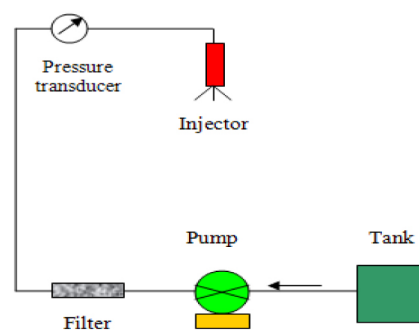


Figure 4. Schematics of single injector per pump layout

The layout in Figure 4 is used commonly in light vehicle, medium and heavy truck applications where only a single injector is needed for urea / HC injection. Urea is driven by a pump, through filter and fed to injector whose pressure is mechanically regulated or controlled by varying pump RPM per pressure transducer readings. Such layout is