

SI Engine Hardware and Software Design for High Power, Low Emission Applications

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ABSTRACT

High technology, spark ignition direct injection (SIDI), engines are currently capable of achieving optimum horsepower and ULEV emissions levels. However, to meet the requirements of modern automotive powertrains, the task of increasing power density, improving fuel economy and reaching SULEV2 emissions is much more challenging. To achieve this, direct injection (DI) fuel systems offer the greatest precision and flexibility for engine fuel control. Features like high pressure start and improved catalyst heating, through multiple injections per combustion cycle, produce low engine-out emissions without the need for a secondary air injection system. This paper describes the analytical and experimental work done to achieve SULEV emissions levels for a twin-turbocharged derivative of General Motors (GM) high feature V6 engine.

INTRODUCTION

Customer demand for increased performance and improved fuel economy is increasingly present across the range of passenger vehicles, while regulations are requiring lower emissions. Advanced technology in engine design and control is a key enabler to improve these simultaneously. Modern gasoline direct injection

systems consist of either solenoid or piezo-electric injectors typically mounted either in the center of the combustion chamber or to the side at an angle. The direct injection system, in this paper, utilizes the wall-guided approach: side mounted multi-hole solenoid injectors with the piston bowl directing the injected fuel towards the centrally mounted spark plug during stratified modes of operation.

Different combustion modes are possible by injecting during either the induction stroke, compression stroke, or both depending on the combustion temperature, torque, and exhaust heat flow requirements. The dual injection HSP (Homogenous Split) mode, used on the SIDI vehicle presented in this paper, is for quick catalyst light off via high heat flow during the after-start warm-up. Injecting during the compression stroke, with a wall guided spray, creates a rich mixture near the spark plug when ignition is desired. This allows stable combustion with further retarded spark timing than possible with port fuel injection (PFI) systems.

VEHICLE HARDWARE DESCRIPTION

The base engine for this vehicle from which data is presented is a 3.6L (94.0 mm x 85.6 mm) 60 degree V6 with dual independent hydraulic camshaft phasing and 4 valves per cylinder.

The engine management system (EMS, consists of engine control unit and algorithms, fuel system, sensors and actuators) is a torque-based system that controls the positions of the intake and exhaust cams, throttle, and waste gate positions based on inputs from the various sensors and the pedal demand of the driver. Air fuel ratio is closed-loop controlled utilizing signals from a mass-air-flow meter and a wideband lambda sensor positioned in front of the close-coupled catalyst. The EMS controls injection duration, injection timing, fuel pump delivery, fuel-rail pressure and ignition timing.

The fuel system, for the SIDI application in this paper, includes low and high pressure circuits. Components for the low-pressure circuit include the in-tank fuel pump module (fuel pump, tank level sensor, fuel filter, fuel pressure regulator) and shutoff valve. Fuel pressure, on the low circuit, operates at 0.05 MPa. The high-pressure circuit, Figure 1, utilizes components that are designed for increased fuel pressures up to 15 MPa. The Bosch fuel components include:

- High pressure fuel pump
- Fuel pressure sensor
- Two fuel rails, for the V6 configuration
- Fuel rail cross-over line
- Pressure relief valve
- Multi-hole solenoid injectors, one per cylinder

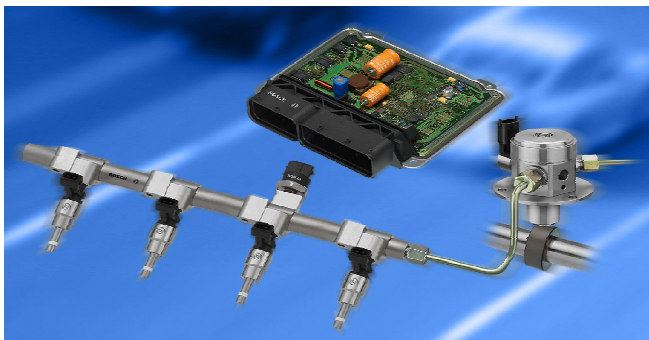


Figure 1. Bosch DI Motronic system hardware.

The fuel system is demand controlled; only the fuel quantity required to maintain a commanded fuel rail pressure is delivered each stroke of the high pressure pump. This allows the system to run without a return line from the high pressure rail. The high-pressure pump, which is driven by a separate camshaft lobe, utilizes electromechanical control for fuel system pressure and delivery. Fuel pressure is monitored in the fuel rail via the pressure sensor.

The Bosch Motronic MED 9 engine management system was used for engine control. Figure 2 shows a typical setup for sensors and actuators in a turbocharged SIDI system.

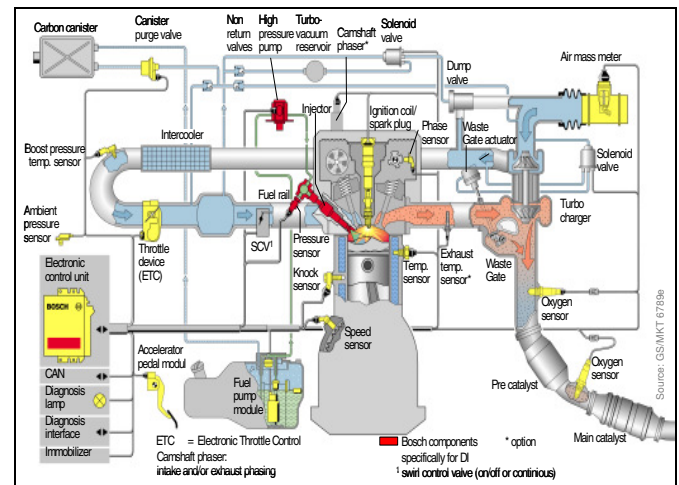


Figure 2. Diagram of Bosch Motronic SIDI turbocharged system layout.

ENGINE AND COMBUSTION DESIGN

The basis of our engine is a GM 3.6L High Feature V6 (HFV6). The 3.6L engine includes intake and exhaust camshaft phasing with 50 crank angle degrees of range per camshaft and a 10.5:1 compression ratio. The DI fuel system includes a single Bosch high pressure fuel pump capable of 15 MPa fuel pressure. The camshaft drive for this application utilizes 4 lobes to meet the increased fuel flow demand of the higher power engine. The ignition system was upgraded from a 45mj coil to a higher energy 65mj output [6]. This assists in providing a stable combustion, at retarded spark angles, necessary for a faster enleanment after start and the highest possible heat flow for catalyst light off.

The SIDI base engine combustion system, employed in the naturally aspirated (N/A) engine, relies heavily on the spray performance of the fuel injector and its match to the mixture motion generated by the intake ports. Initial spray pattern layout was developed from combustion chamber CAD data. With the importance of high pressure start and HSP modes, Figure 3, CFD modeling is employed to assess the interaction of the spray pattern and piston bowl. Targets for equivalence ratio at the spark plug are set at typical ignition timings used during HSP mode.

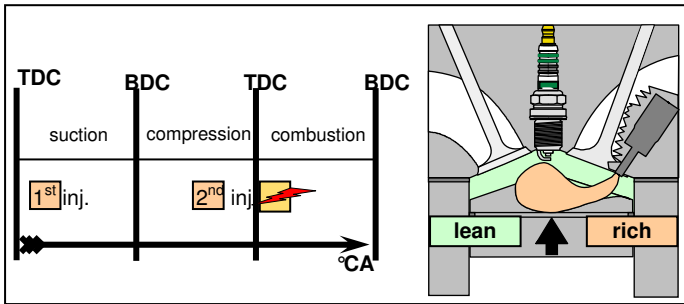


Figure 3. Homogeneous Split Injection (HSP) mode

This engine was upgraded from the regular production SIDI HFV6 with forged pistons that include a “catalyst heating optimized” crown feature. Much time was spent focusing on injector spray targeting and piston design to greatly reduce HC during cold start. By reducing formation of HC in the combustion chamber, start emissions are greatly improved. After many iterations and changes, the optimized designs were implemented. These include:

- Direction and quantity of fuel spray into the piston bowl.
- Piston bowl geometry to produce efficient motion of fuel flow to the spark plug.
- Remove sharp corners of the piston crown.
- Production feasibility and cost.

Figure 4 shows the new layout of the injector spray and piston design. These hardware changes reduce piston crevice volumes [4] and guide the fuel toward the spark plug in a fluid motion.

The engine was also updated with stronger connecting rods and an optimized intake manifold. The exhaust system is comprised of Ricardo designed stainless cast exhaust manifolds and twin Borg-Warner single scroll turbochargers, with twin air-to-air charge coolers.

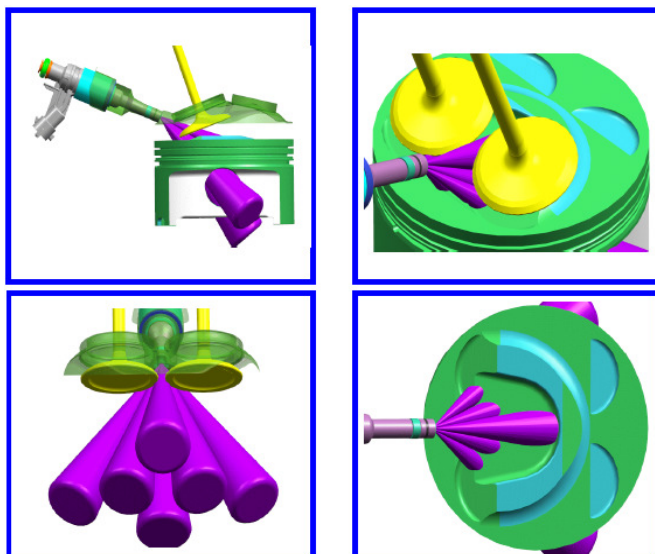


Figure 4. Redesigned engine hardware.

The turbocharged SIDI combustion system development has additional requirements. Injector static flow rates are typically increased from 17.55cc/sec to 22.5cc/sec which leads to increased wall wetting at lower speed high load conditions. Development of the spray pattern and level of mixture motion were required to address these issues.

The turbocharged SIDI engine system is used in a vehicle that has been named “DI BOOST”. This vehicle, as shown in Figure 5, was the subject of discussion by Woldring [3] to show the performance potential of a boosted V6 when compared to a V8, and the fuel economy benefits of engine downsizing.



Figure 5. DI BOOST vehicle – Cadillac CTS-V

EXHAUST AFTERTREATMENT SYSTEM

For DI BOOST, three different light-off catalyst systems were evaluated; the details of each are shown in Table 1. The exhaust system is dual leg configuration with one close coupled converter per bank and two under-floor catalysts. The engine system parameters were changed to investigate the influence of precious metal loading and the effect of perforated foil substrates. The perforation feature minimizes the thermal mass to achieve fast catalyst light off during engine cold start. The exhaust after-treatment system was designed to overcome the following challenges:

- Fast catalyst light-off performance during vehicle cold start
- Utilize available space to package close coupled converter systems
- Low flow restriction to achieve engine power targets

The Emitec perforated metal foil substrates shows improved light-off performance compared to the non-perforated foil substrates, due to the lower thermal mass and the mixing of the gases.