

Fuel Efficiency Improvements from Lean, Stratified Combustion with a Solenoid Injector

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ABSTRACT

In light of the growing emphasis on CO₂ emissions reduction, Delphi has undertaken an internal development program to show the fuel economy benefits of lean, stratified combustion with its outwardly-opening solenoid injector in a vehicle environment. This paper presents the status of this ongoing development activity which is not yet completed. Progress to date includes a logical progression from single- and multi-cylinder dynamometer engines to the vehicle environment. The solenoid-actuated injector used in this development has an outwardly-opening valve group to generate a hollow-cone spray with a stable, well-defined recirculation zone to support spray-guided stratification in the combustion chamber. The engine management system of the development vehicle was modified from series-production configuration by changing the engine control unit to permit function development and calibration. The resulting full-size, V6-engine vehicle achieves significant fuel savings compared to homogeneous stoichiometric operation, while showing the potential to be the best-value Powertrain solution through the innovative use of solenoid injector technology.

INTRODUCTION

Lean, stratified combustion produces fuel savings in gasoline spark-ignited, direct injection (SIDI) engines for several reasons. First, unthrottled operation allows for a significant pumping loss reduction, especially at lower loads. Second, the lean mixture being compressed has

a higher ratio of specific heats, commonly referred to as gamma. This allows for a more efficient compression and expansion process. Third, there are lower wall heat losses in the cylinder because of the centralization of the mixture away from the walls. In addition, the ability to operate with a higher compression ratio due to the use of direct injection brings efficiency advantages. A more detailed thermodynamic comparison of the advantages of this type of combustion can be found in [1].

In this paper, we discuss spray-guided stratified combustion, for which there are a number of component-level and system-level requirements. For a normally aspirated engine, a centrally-mounted direct injector with a hollow-cone spray is needed. The spark plug is mounted such that it can ignite a fuel-rich "recirculation zone" created by vortices just outside the spray cone. The fuel system has a high-pressure gasoline pump in addition to the tank-mounted lift pump. In order to produce the desired spray characteristics in the cylinder, a rail pressure typically in the range of 200 bar is used. For engine-out NO_x emission reduction, exhaust gas recirculation is desirable. Due to the high intake air flow rates associated with lean operation, a high-flow EGR valve is needed in order to introduce meaningful amounts of exhaust gas. The use of camshaft phasers complements the external EGR by producing in-cylinder exhaust gas residuals. From an exhaust emissions perspective, a key sub-system which must be added is lean NO_x aftertreatment, typically in the form of a NO_x storage catalyst (NSC).

OUTWARDLY-OPENING SOLENOID INJECTOR

Spray-guided combustion has higher requirements than homogeneous direct injection in terms of spray stability, fuel atomization, and the capacity for precisely controlled, closely-spaced multiple injections in order to produce the desired spray characteristics for flammability at the spark plug gap. To fulfill these requirements current production injectors use piezoelectric actuation in conjunction with an outwardly-opening valve. The objective of the Delphi fast single coil injector development was to maintain the performance benefit of the piezoelectric systems over conventional injection technology without the additional cost associated with the piezoelectric actuator and high-voltage electronic driver circuits. The resulting injector has been designated the Multec 20.

The Multec 20 injector shown in figure 1 is based on conventional single-solenoid direct actuation of the pintle. In order to drive the large valve diameters required for spray stability in stratified operation, the Multec 20 injector uses a pressure-balanced valve concept, which allows valve operation which is nearly independent of system fuel pressure. Similar to piezoelectric injectors, valve closing is powered by a spring. To ensure a fast closing without valve rebound and associated after-injection, the Multec 20 has implemented a novel decoupled valve-armature concept. This minimizes impact loads between seat and pintle and decouples the movement of the pintle and armature during the closing event. Because the injector does not require a physically long piezo element and associated thermal compensation hardware, there is packaging flexibility available in applications where a shorter injector is advantageous.



Figure 1: Multec 20 Injector Prototype

The requirements on the Multec 20 actuator are more demanding in terms of transient response and force than for solenoid multi-hole injectors. Yet, the target of packaging the actuator within the envelopes of both standard multi-hole and piezoelectric injectors was achieved while using conventional materials and driver currents. A particular focus was placed on material choices in the injector to be compatible with bio-fuels. The use of stainless steels and the avoidance of elastomers are two examples.

Multiple-injection capability was one of the injector's primary design goals. For spray-guided combustion, applying multiple short pulses to deliver the fuel reduces penetration and produces a superior fuel-air mixture in the area of the spark plug gap. Figure 2 shows a comparison of single, double, and triple pulse injections with the same total delivered fuel mass of 20 milligrams. It is clearly evident that the double and triple pulses reduce penetration and keep the fuel closer to the spark

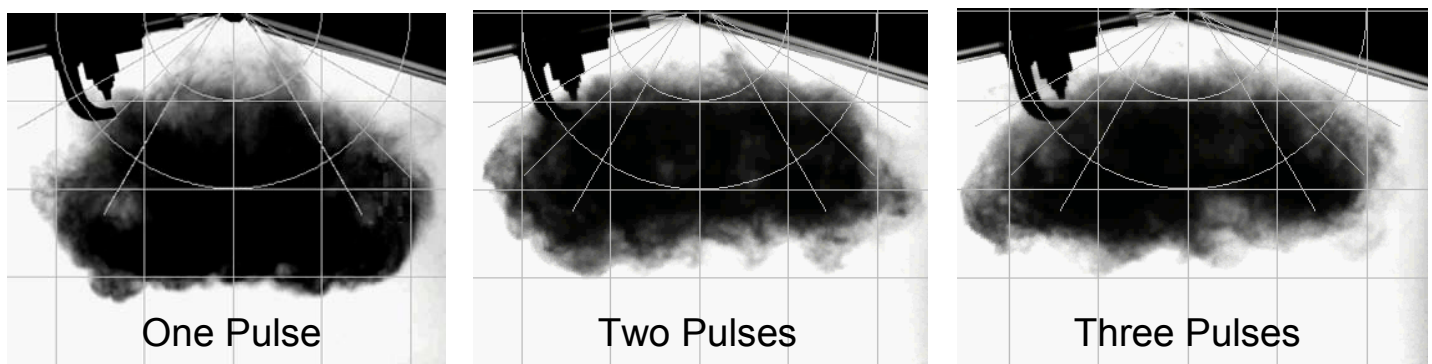


Figure 2: Pressure Chamber Spray Comparison Between Single, Double, and Triple Pulses with the Same Total Fuel Mass Delivered

plug. In the single pulse picture it can also be seen that the fuel tends to be pushed past the spark plug gap instead of dwelling closer to it and obscuring it as occurs in the second and third pictures.

Figure 3 shows the pintle stroke, the applied current, and the logic trigger signal for a triple injection sequence. This figure demonstrates the ability of the injector to operate close to present piezoelectric injector performance. In particular, hydraulic delays of less than 200 μ s between subsequent pulses are achievable. The second and third pulses are shown in the “ballistic” region, with the injector starting to close before fully opening. Use of this injector in the ballistic regime is possible and tests have demonstrated repeatability of mass delivery with dispersion < 10%. Opening flight times and closing responses are also comparable to piezoelectric injectors presently in production.

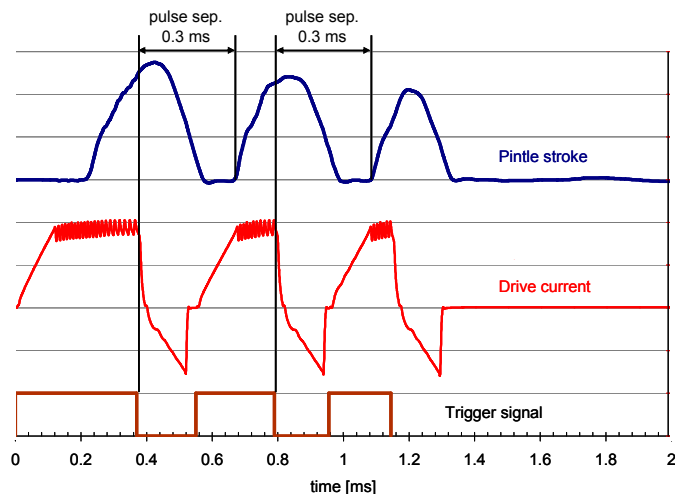


Figure 3: Multec 20 Multi-Pulse Performance

Another focus of the injector development was control of the spray shape and stability under the high pressure and temperature in-cylinder conditions of the compression stroke. The outwardly-opening valve creates a small conical gap in which a thin, hollow-cone spray sheet develops. This spray sheet then breaks up into finely atomized droplets. A key requirement is that the spray develops and maintains a recirculation zone outside the conical envelope so that fuel is transported to the spark plug location marked in Figure 4 with a circle. A computational fluid dynamics (CFD) simulation activity using the tool AVL Fire was used to augment understanding of the spray phenomena. Good agreement between pressure chamber shadowgraphy and the simulation results was achieved, as shown in Figure 5.



Figure 4: Spray Formation Recirculation Zone

MULTI-CYLINDER ENGINE APPLICATION

The injector development activity insured that the solenoid injector has the essential fundamental capabilities of spray and speed of response in both single-pulse and close-coupled, multi-pulse operation. It is relevant also to comment that the base injector development included extensive work in a single-cylinder engine.

Therefore, the next step in the system development was application of the injectors to a multi-cylinder engine. For this activity, Delphi selected the Mercedes 3.5 liter M272 DE V6 engine. This engine is in series production with spray-guided combustion and it features a central mounting of the injector as well as a spark plug location adapted for spray-guided combustion. The M272 is equipped with a 200-bar fuel injection pump, dual intake and exhaust camshaft phasers, and a variable intake manifold [2].

INJECTOR SPRAY POSITIONING

For application of the injector in the engine, the correct physical positioning of the spray recirculation zone for comparable overlap of the spark plug gap was accomplished with several considerations driven by the slightly-smaller exit diameter of the Multec 20 injector compared to the production injector.

- Positioning the injector in the vertical axis to match the position of the nozzle exit in the production application. This positioning is done with the dimensions of the spacer between the injector and the cylinder head.
- Increasing the hardware spray angle of the injector to compensate the slightly smaller valve exit diameter. The spray angle is modified by changing the geometrical dimensions of the injector components in the valve area.