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ANALYSIS OF ELECTRONIC FUEL DIRECT INJECTION SYSTEM IN SPARK-IGNITION ENGINES

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Summary. *Since the invention of the spark-ignition engine, or Otto cycle engine, extensive studies have been accomplished in order to reach high performance, low emission and good fuel economy, simultaneously. Recently, automotive industries have restarted the production of electronically controlled engines with fuel direct injection systems. The technology of direct injection presents characteristics that contribute in a positive way to reach the objectives above mentioned. This paper presents the state-of-the-art of direct fuel injection in SI engines, the current technology to make possible its accomplishment, the characteristics of the engines using this system and a comparative experimental study between this system and the indirect fuel injection one.*

key-Word*: Direct fuel injection, Mixture, Spark-ignition.*

1. INTRODUCTION

The history of the direct fuel injection in spark-ignition (SI) engines is as old as the own engine. Research in this area has been accomplished since before Second World War, using for this the same technology as that utilized in the Diesel engines (Hildebrand Jr., 1998).

Before the invention of sophisticated carburetors, some of the highly boosted air plane engines adopted direct injection systems using the fuel injection technologies for diesel engines.

This technology disappeared with the progress of carburetors. During this period, the engines with direct injection adopted the strategy of early injection, that is, the fuel was injected during the intake stroke to prepare the homogeneous mixture. Consequently, it was not possible to obtain a good economy of fuel (Iwamoto, 1997).

According to Glöeckler *et al.* (1981), in 1930, the German Aviation Research Institute began a concentrated development program in fuel direct injection in the combustion chamber, using an injector of diesel engine. The goal was to achieve optimum cylinder filling with resulting maximum engine power output. Even with manifold (or port) injection, more air is inducted than with a carburetor, because the latter requires a throttling element in the intake passage to create fuel delivery conditions. With direct injection only air is present until injection, even the necessary fuel volume is occupied by air. This experiment had as result an increase of the order of 4% in power.

In 1931, Taylor *et al.* accomplished tests with direct injection in a SI engine in order to compare the results with those obtained from carburetor system. They had as a result an increase from 7 to 11% in the maximum power and a significant improvement in the specific fuel consumption.

In 1935, Rothrock and Waldron, of National Advisory Committee for Aeronautics (NACA), made tests with direct injection in order to analyze the effects of the advance angle of the fuel injection, temperature of the engine and combustion speed in a compression–ignition engine.

During Second World War, the Germans used extensively the direct injection in the engines of its war planes (Hildebrand Jr., 1998).

In 1957, Dolza *et al.*, on a single-cylinder unit (Fig. 1), accomplished tests with direct injection with the intention of comparing this system and that of conventional carburetor in the different conditions of speed, load and temperature of the engine.

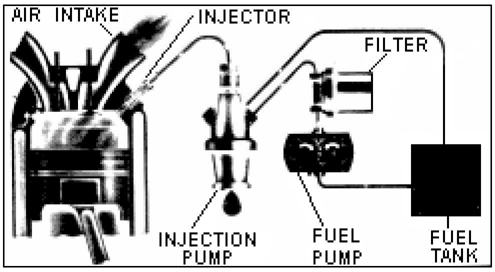

Figure 1: Single-cylinder unit with direct fuel injection system.

Davis *et al.* (1961), of Texaco Research Center - Beacon, developed a engine with high thermodynamic efficiency associated with combustion of lean mixtures (economy), using direct injection into the cylinder. This process, called TCP (Texaco Combustion Process), had as main characteristic the swirl of the mixture air-fuel in the combustion chamber. The swirl happened due to the angle between the fuel injector and the wall of the cylinder. The objectives of these researches were reached, however the production of engines that used this process was not possible due to the high cost of production.

In 1963, Hussmann *et al.* tested a direct injection system to analyze the behavior of the engine during the operation with stratified charge and the effect of the variation of the lag of time between injection of fuel and ignition of the mixture.

From 1965 to the end of the 80's, other engines with this system were developed, like MAN-FM in 1968, the Ford-PROCO in 1971, Daimler-Benz OCC in 1976 and the IRVW-Future, of Volkswagen, in 1989 (Queiroz & Tomanik, 1997). According to Iwamoto (1997), in this period extensive studies continued being accomplished with the direct injection system in order to reach a high fuel economy. It was concluded that engines with direct injection system should be operated in an extremely lean condition, stratifying the charge and preparing a mixture slightly rich close to the spark-plug. For this reason, several combustion concepts in stratified load were proposed in this period. Those concepts adopted a configuration in which the spark-plug is located very close to the fuel spray. Although it has been confirmed that a stable combustion could be accomplished with this configuration, the following problems hindered that these concepts were developed for mass production:

Hidrocarbon emission: great amount of hidrocarbon was emitted because it was difficult to complete the combustion.

Spark-plug fouling: in case of narrow spacing, the liquid fuel spray or the over-rich mixture was located at the spark plug, resulting in the formation of soot. Soot was accumulated in the plug gap and caused the ignition fouling. Although higher energy ignition systems have sometimes shown the effects of reduced ignition fouling, problem associated with the deterioration of the durability of the spark plug due to higher ignition energy could not be solved.

Poor performance: the injection timing variation range realized by the mechanical fuel injection equipment employed in this period was limited, and the switching from late to early injection strategy was not possible. Consequently, these engines should be operated with the stratified charge even at the highest load range. In order to prevent the soot emission, the air-fuel ratio should be maintained high, resulting in poor performance.

Dilution of the lubricating oil: it was difficult to prevent the liquid gasoline droplets to impinge on the cylinder liner or on the piston surface. Gasoline on the cylinder liner diluted the lubricating oil on the cylinder liner. Gasoline on the piston surface was captured in the piston crevice and also diluted the lubricating oil.

Accumulation of sediments in the combustion chamber: with this injection system, was formed a film of liquid fuel on the piston surface causing the accumulation of sediments in the combustion chamber.

After 1990, the economy of fuel has been the main objective of the automobile industry, because this is the key factor for the economy of energy and reduction of CO, one of the most noxious gas to the ozone layer. To reach this objective, researches in the energy area started to establish new technologies of direct injection that can really be applied to the engines produced (Iwamoto, 1997).

According to Automotive Engineering magazine (1997), the main automobile industries already work with fuel direct injection systems in some of its engines. It is the case of Mitsubishi, Toyota, Audi, Chrysler and Mercedes-benz.

Mitsubishi introduced its Gasoline Direct Injection (GDI) engine to the Japanese market in August 1996. Direct gasoline injection allows the engine to operate at very lean mixtures (up to a 35:1 air/fuel ratio) during highway cruising. This helps to improve fuel economy up to 30% at part throttle, which allows the GDI car to get better fuel economy than the 2.0-L turbo diesel Galant offered in the Japanese market. At high loads, the engine operates at near-stoichiometric ratios.

Toyota began a limited production run in 1997 of its D4 (direct injection 4 stroke) gasoline engine in its 40th-anniversary-edition Corona Premio compact sedan for the Japanese market. The D4 shares its basic design with the company's 3S-FE four-cylinder engine. It has a compression ratio of 10:1 for maximum power and torque of 107 kW (6000 rpm) and 196 Nm (4400 rpm), compared with the convencional engine's 9.5:1 CR, 103 kW, and 186 Nm at the same engine speeds. Notable diferences are greater fuel pressure (8.0-12.0 vs. 0.33 MPa) and variable instead of fixed intake valve timing.

Other factors that have been contributing to the progress of the studies in this area are the progresses obtained in the technologies of aftertreatment of combustion gases and the improvement of the engine control systems and of the electronic fuel injection systems. To strengthen the need of continuing improving this system, there are still laws that regulate the emissions of the exhaust gases of the engines.

2. DIRECT INJECTION SYSTEM CONFIGURATION

The direct fuel electronic injection system (FDI) in the combustion chamber of the cylinders of a SI engine(Fig. 2) is a concept that offers a lot of advantages in relation to the most sophisticated engines with indirect injection system (FII). The thermodynamic potential to reduce the fuel specific consumption, allied with the advantages of the fast start, improved responses in engine transient operation and facilitated a larger precision in the control of the mixture air-fuel (Zhao *et al*., 1997). An illustrative comparison between the systems FDI and FII is presented in Fig. 3.

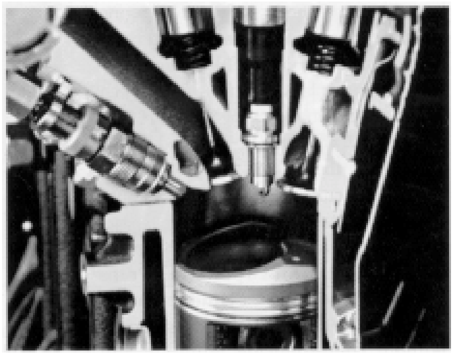

Figure 2: Cutaway view of the Toyota D4 engine showing FDI system.
Source: Yamaguchi (1996)

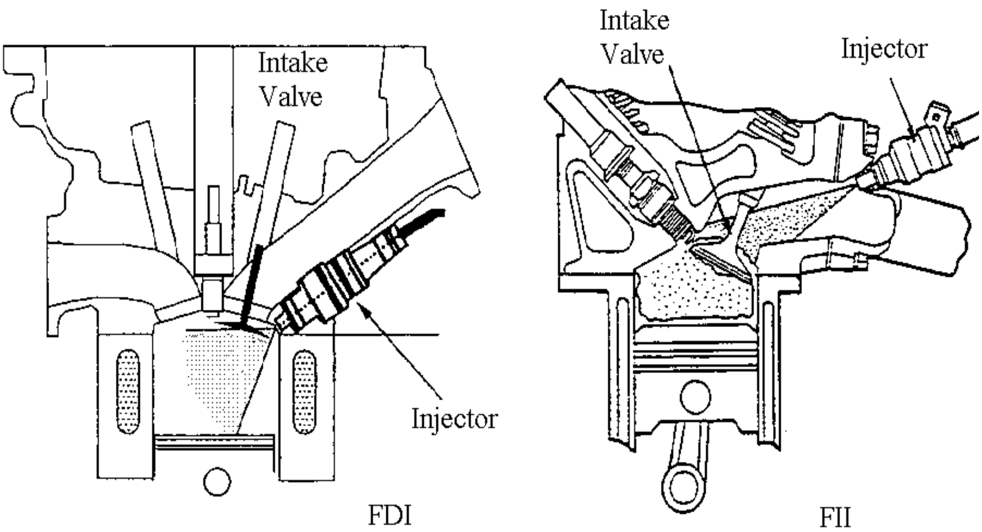

Figure 3: Comparison between the systems FDI and FII.
Source: Zhao et. al. (1997).

For Harada *et al*. (1997), the gasoline spark-ignition engine with system of direct injection is the most efficient, as much in fuel economy as in performance. This system presents the following advantages:

- high acceleration response and superior transient driveability even under cold temperature conditions because of the direct fuel injection into the cilinder;
- high volumetric efficiency and anti-knock characteristic because of lower temperature of charge air and;
- high thermal efficiency because of lower pumping loss and heat loss.

Kowalewicz (1984), mentions other advantages:

- smaller rate of emissions;
- larger economy, mainly in partial loads;
- possibility to burn fuels of low octane index.

However, it is important to point out that to obtain the advantages above mentioned, it is necessary that the fuel is injected with pressures of the order of 10 to 50 MPa (Lenz, 1992).

3. FDI ENGINE TESTS

It was used for this research an alcohol SI engine, 4 cylinders in line, 1588 cc, compression rate of 13.7:1 and with FII system. This system was modified later on for the FDI for obtaining the comparative data.

Besides the basic equipments already existent in the laboratory, the following components were used for these tests:

- Foucault currents dynamometer for joining of the engine;
- alcohol direct injection system;
- analogical pulses generator to activate the injectors;
- gravimeter system for measuring fuel consumption;
- cooling system of the engine; and
- computerized data acquisition system.

The fuel supply system used in this engine after the modification is composed of conventional injectors and electric bomb, used in the FII systems.

Previously tests were accomplished with the engine using the FII system in order to collect data on torque, power, specific fuel consumption and global thermal efficiency of the engine. With these results in hands, the engine was modified to use the FDI system and, then, the tests were repeated for obtaining new data.

4. RESULTS AND DISCUSSION

The graphs below present the comparative results obtained for the systems of direct and indirect injection.

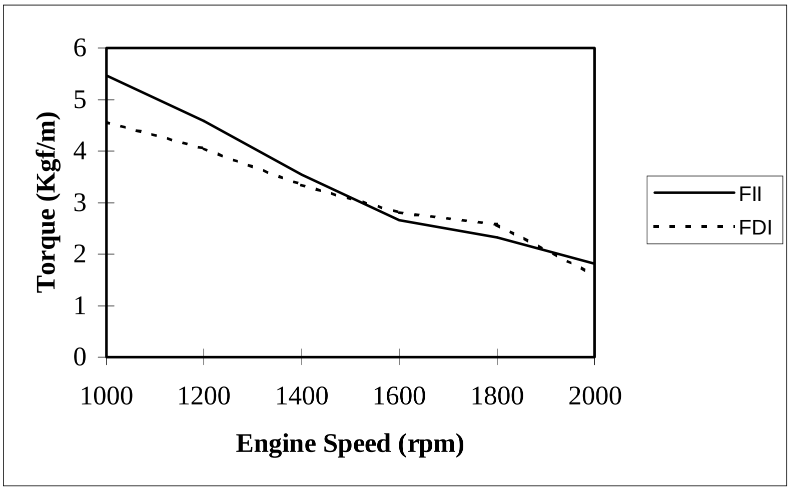

Figure 4: Torque as a function of the rotational speed for the FDI and FII systems.

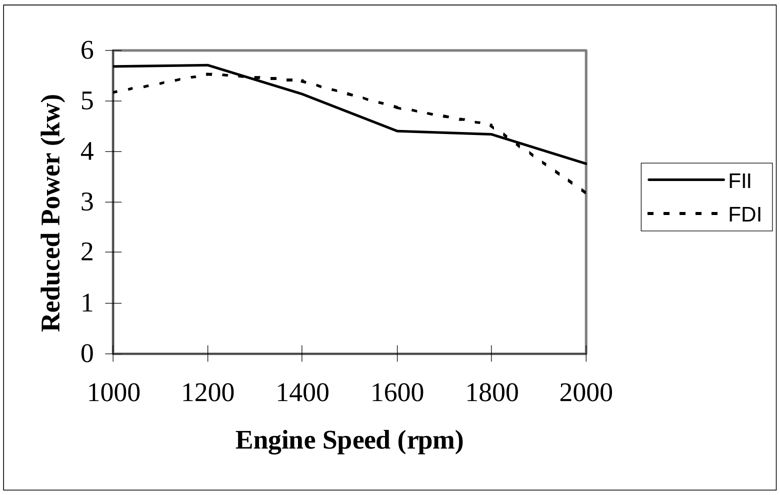

Figure 5: Reduced power as a function of the rotational speed for the FDI and FII systems.

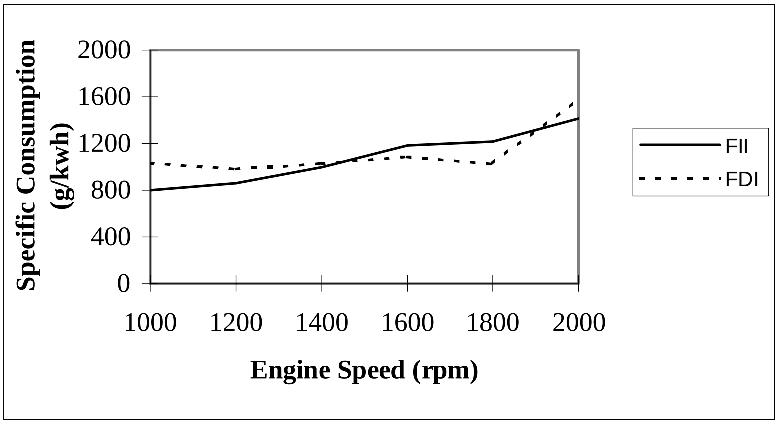

Figure 6: Specific consumption as a function of the rotational speed for the FDI and FII systems.

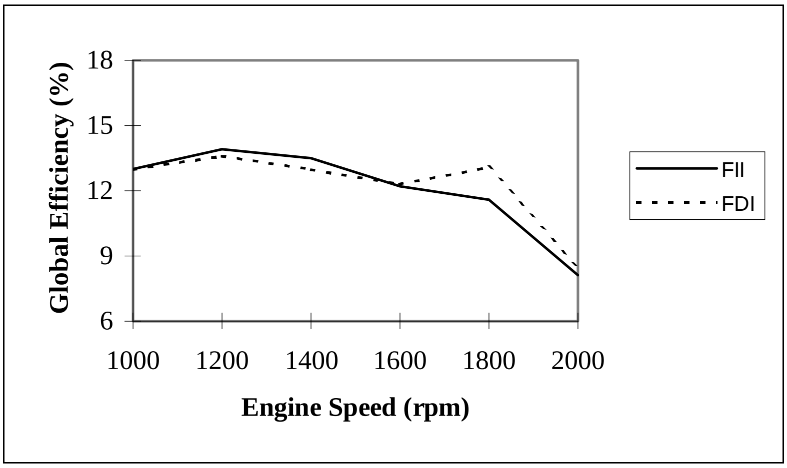

Figure 7: Global efficiency as a function of the rotational speed for the FDI and FII systems.

The system running with FDI, controlled by the analogical pulses generator at steady state condition, presented a power and torque fall between 1000 and 1200 rpm in relation to its operation with FII system.

It is observed that there was little use of the energy supplied by the fuel at 1000, 1200 and 2000 rpm with the FDI system. On the other hand, when controlling the engine by FII, power, torque and global efficiency decreased at 1400, 1600 and 1800 rpm, and the fuel hourly consumption remained equal, or was higher for the engine working with direct injection.

As combustion depends on the homogeneity of the air-fuel mixture, the fall in power and torque, the low global efficiency and high specific consumption (at 1000 and 1200 rpm) can be attributed to the excess of liquid fuel injected into the cylinder. The pulses generator, responsible for activating the injectors, supplied the cylinders with an extremely rich mixture at those speeds. With relation to the speed of 2000 rpm, the same situation happened, probably due to the little time the FDI system allows for the formation and homogenizing the air-fuel mixture, and also due to the fact that the fuel injection took place at low pressures, not allowing fuel droplets of appropriate size being obtained.

The presence of drops of big diameter in the fuel injected spray makes difficult its vaporization, that, in this case, only happened by the heat exchange with the air warmed up by the work of compression of the engine.

5. CONCLUSIONS

This paper presented the state-of-the-art of direct fuel injection technology. Previous tests using low pressure fueling were presented. Even using low injection pressures and an analogical pulses generator to activate the injectors, it was possible to obtain a considerable torque and power gains at 1400, 1600 and 1800 rpm, when the pulses generator was more efficient.

For the conditions where a slight fall in the torque and power happened, the use of improved injectors and electric bomb of fuel and combining with an electronic injector controller, could allow for the possibility to improve the formation and homogenizing of the air-fuel mixture increasing the global thermal efficiency, torque and power.

At low pressure, the FDI system could present good advantages combined with low price and could be an interesting alternative to high pressure FDI systems.

Thus, through research and development to obtain the advantages mentioned in this paper, the system of direct injection will become, shortly, used in large scale in the engines produced in the automobile industry.

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