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Direct Injection Optimized by Electronic Control: A Real Benefit to the Automotive Industry

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ABSTRACT

The development of The automotive industry is strongly driven by the need for more efficient, economical, and cleaner engines. In this context, direct fuel injection combined with electronic control represents a major evolution in internal combustion engine fuel systems. Unlike conventional injection systems, electronic control enables precise adjustment of the injected fuel quantity, injection pressure, injection timing, and, in some architectures, the number of injections per engine cycle. This level of control makes it possible to optimize the air-fuel mixture formation and combustion according to engine speed and load.

This paper analyses the technical and industrial advantages of electronically controlled optimized direct injection. The analysis shows that this technology can contribute to improved fuel economy, higher specific power, and increased thermal efficiency. In gasoline direct-injection engines (GDI), the technology is particularly associated with improved fuel economy and higher power output compared with some port fuel injection architectures.

However, direct injection also presents challenges, including potentially higher particulate emissions, injector deposits sensitivity, and increased electronic calibration complexity. Advances in injection strategies, injector design, engine control, and exhaust after-treatment systems have significantly reduced these limitations. Electronically controlled direct injection can therefore be considered a real advantage for the automotive industry, provided that its development is supported by accurate calibration, appropriate maintenance, and effective emission-control systems.

KEYWORDS: *direct injection, electronic control, internal combustion engine, fuel injection, engine control unit, thermal efficiency, fuel consumption, emissions, automotive industry, GDI, diesel.*

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1. INTRODUCTION

The internal combustion engine remains an important technology in the automotive industry, in particular in internal combustion engine vehicles and hybrid. However, the evolution of the environmental and economic requires manufacturers to simultaneously search a reduction of fuel consumption, improved performance and a reduction of pollutant emissions [1].

In this context, the fuel-injection systems have undergone a considerable evolution. The passage of mechanical systems, or indirect to direct-injection systems are electronically controlled and has allowed to significantly improve the accuracy of the fuel metering.

Direct injection is to introduce the fuel directly into the combustion chamber, unlike indirect injection

where the fuel is injected in the intake duct before entering the cylinder.

In gasoline engines, direct injection, commonly referred to as Gasoline Direct Injection (GDI), the fuel is injected at high pressure directly into the cylinder. This architecture allows for better control of mixture formation and reduce some of the delays associated with the transportation of fuel. The literature also indicates gains of consumption and thermal performance compared to some of the architectures with indirect injection [2].

However, the benefits of direct injection are not solely derived from the injector itself. They are highly dependent on the ability of the electronic system to determine when, how much and at what pressure the fuel must be injected.

The association between direct injection and electronic control is therefore an essential element of the modern automobile technology.

An automobile engine operates in conditions of extremely variable.

The engine can change quickly, just like:

- the load of the engine;
- the temperature of the engine;
- the inlet pressure;
- the application of the couple;
- the external temperature;
- the driving conditions.

An injection system, which would always provide the same amount of fuel could not ensure an optimal combustion under all conditions.

The electronic control allows you to resolve this issue.

The engine control unit receives information from various sensors and determines the strategy of injection is appropriate.

The problem can therefore be formulated as follows:

The extent to which the optimization for electronic direct injection is a real advantage to improve performance, fuel economy and emissions of automotive engines ?

The general Objective is to analyze the technical advantages of direct injection optimized by the control electronics in the automotive industry.

Thus, in our study we will:

- explain the principle of the direct injection;
- present the role of the electronic control;
- to analyze the influence of the strategy of injection on the combustion;
- to examine the effects on the consumption of fuel;
- analyze the effects on the performance of the engine;
- to study the consequences on emissions;
- identify the limitations of the technology;
- show the prospects for the development of the injection motor.

2. MATERIALS AND METHOD

2.1. Thermodynamic Cycle diesel

The operation of the diesel engine is embodied in a thermodynamic cycle four-stroke, a sequence of events, physical and chemical, which takes place for each cylinder (Figure 1.1), fundamental described in 1862 by the French engineeralphonse beau de rochas:

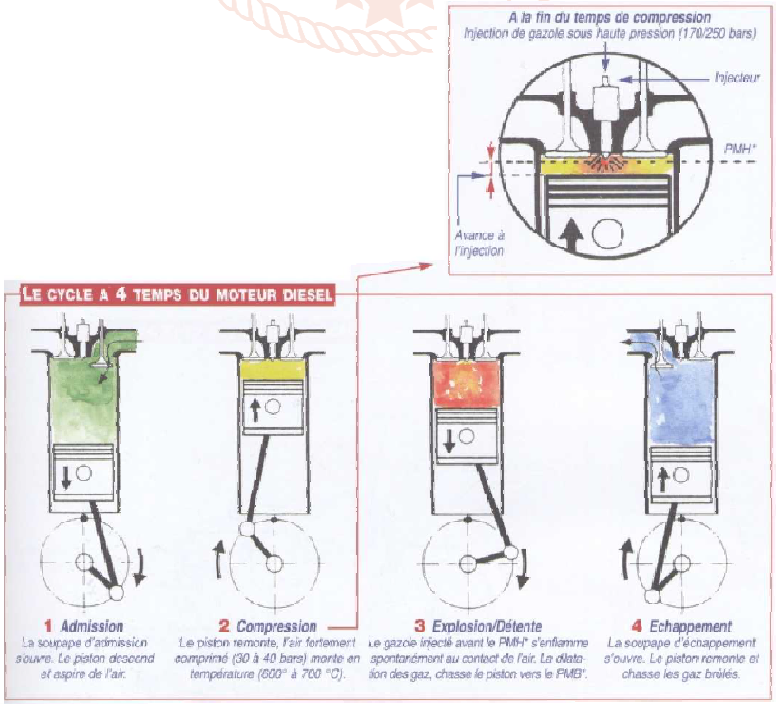


Figure 1.1.the four-stroke diesel engine [3]

1st time: Inlet (Suction)
The piston performs its downward (top dead center-TDC - the bottom dead-PMB). Simultaneously, the inlet valve opens, allowing the cool air and filtered, often under pressure thanks to the turbocharger, to penetrate and fill the cylinder. The exhaust valve remains closed.

2nd time: compression
The piston goes up (from BDC to TDC), while all of the valves (intake and exhaust) remain closed. The air trapped in the cylinder is highly compressed. Because of this adiabatic compression, the pressure increases dramatically (up to commonly 60 to 80 arms) and, even more critical, the temperature rises dramatically, often between 700°C and 900°C. It is this elevated body temperature, which is the fundamental requirement for the self-ignition of the diesel fuel.

3th time: Combustion-relaxation Time (motor)
Shortly before the piston reaches the TDC of compression (typically 5 to 15 degrees crankshaft before TDC), the diesel fuel is injected under very high pressure through the injector. On contact with the superheated air, the fuel atomizes and self-ignites quickly. The combustion progressive generates a massive release of energy, resulting in a sudden increase of the pressure and the temperature of the gas in the cylinder. This pressure pushes violently the piston down (from TDC to BDC), thus producing the mechanical work required for the rotation of the crankshaft. What time is the only producer of motive power.

4th time: Escaping
The piston starts its up stroke (BDC to TDC), the exhaust valve opens, allowing exhaust gas, in which the pressure is still significant, to be expelled from the cylinder to the exhaust manifold and, subsequently, to the after-treatment systems. The inlet valve remains closed.

Representation on a diagram of a PV (Pressure-Volume): this cycle is conveniently represented on a diagram P-V, where the y-axis represents the pressure and the x-axis the volume of the cycle. Each point in the cycle describes the thermodynamic state of the gas. The area bounded by the closed curve of the cycle represents the net work produced by the engine in each cycle. The diesel cycle idealized is characterized by combustion at constant pressure, which distinguishes it from the Otto cycle (combustion at constant volume) and gives it a theoretical yield higher compression ratios equivalent. The key parameters of the real cycle, as the compression rate density (ratio between the total volume and the volume of the combustion chamber at TDC, typically higher for the diesel), the pressure of the end of the compression, and the temperature of the gas, are fundamental for the effective functioning[5].

2.1.1. Principle of direct injection

In a direct injection engine, fuel is introduced directly into the combustion chamber.

This configuration has several advantages compared to injection in the intake duct.

Direct injection allows:
- a better control of the time of injection;
- a more precise control of the quantity of fuel;
- a better adaptation of the injection to the conditions of operation;
- a possibility of multiple injection;
- an improvement of the mixture formation;
- an optimization of the combustion.

In engines, GDI, high pressure and precise control of the injection allow you to manage the formation of the fuel-air mixture directly into the cylinder. The strategies of mixture formation and combustion, however, are complex and require an accurate calibration.

2.2. The electronic control of the injection

The electronic control is the brain of the system.

It is usually provided by an electronic control unit of the engine, known as ECU or ECM.

The ecu receives the information from different sensors:
- position of the crankshaft;
- position of the camshaft;
- pressure intake;
- temperature of cooling liquid;
- temperature of the air;
- flow or mass of air.
- position of the accelerator;
- pressure of fuel;
- richness of the mixture;
- content of oxygen in exhaust gas.

From this information, the calculator determines the strategy of injection.

One can simplify the operation according to the scheme:
Sensors → engine control unit → Strategy of injection → Injector → Burning → Sensors exhaust → Correction

This loop function allows you to continuously adapt the combustion.

2.3. Optimized parameters electronically

2.3.1. Amount of injected fuel

The amount of fuel that must be adapted to the amount of air available and at the request of torque.

An excessive amount may result in:
- a high consumption;
- an incomplete combustion;
- a rise in unburned hydrocarbons;
- an increase of particles in certain conditions.

An insufficient amount can cause:
- a loss of power;
- a combustion unstable;
- of misfires;
- an increase of certain programs.

The electronic control allows you to look for a compromise between performance, fuel consumption and emissions[6].

2.3.2. Time of injection

The time at which the fuel is injected plays a crucial role.

According to the operation of the engine, the injection may be performed at different times of the cycle[7].

The modification of the injection timing influence:
- the evaporation of the fuel;
- the formation of the mixture;
- the start of combustion;
- the pressure in the cylinder;
- the yield;
- the emissions.

2.3.3. Injection pressure

The increase of the injection pressure typically promotes a better atomization of the fuel.

The smaller droplets make it easier:
- the evaporation;
- the air-fuel mixture;
- the combustion.

In modern diesel engines, electronic systems, in particular, enable highly accurate control of the pressure and the time of injection. The modern strategies may also use injections pilot, main and post injections.

2.3.4. Multiple Injection

One of the major advantages of the electronic control is the ability to perform multiple injections during a single cycle.

For example:
Injection driver → main Injection → Post-injection

This strategy can be used to control:
- the combustion noise;
- the maximum pressure;
- the emissions;
- the formation of particles;
- the temperature of combustion.

The strategies of multiple injection are part of the methods studied to simultaneously improve performance and reduce emissions.

2.4. Influence on the fuel consumption

One of the main industrial benefits of the direct fuel injection is its potential for improving the fuel economy. In gasoline engines, GDI, some studies report an improvement in the consumption of the order of 5% to 15% relative to some of the architectures with indirect injection, depending on the engine, the operation strategy and the terms and conditions of use [8].

This improvement is mainly explained by:
- a dosing more accurate;
- a better control of the formation of the mixture;
- a reduction of certain losses;
- an improvement of the thermal efficiency;
- a better adaptation of the combustion in the engine load.

It should, however, avoid considering the gain of consumption, such as a universal value: it depends on the engine design and its calibration.

2.5. Influence on power and torque

Direct injection may also contribute to the increase of the specific power.

Direct injection allows a more precise management of the fuel and combustion.

In engines GDI, the literature reports including a specific power and thermal efficiency, higher than some of the configurations with indirect injection [9].

The technology is particularly interesting when it is associated with:
- a turbocharger;
- a compression rate optimized;
- a variable distribution;
- an electronic control advanced.

The industrial becomes to produce more power with a displacement relatively low.

2.6. Influence on pollutant emissions

Direct injection has an important peculiarity: it can improve the efficiency of the engine, creating new challenges in terms of emissions.

In engines GDI, the local conditions of mixture can promote the formation of particles [9].

The research shows that the particulate emissions of the engine GDI can be influenced by:
- the time of injection;
- the injection pressure;
- the fuel / air ratio;
- the temperature of the engine;

- the design of the injector;
- the quality of the fuel;
- the strategy of combustion.

There is therefore a compromise between:
Performance ↔ Consumption ↔ Emissions

Optimization-mail must seek a solution to satisfy simultaneously these different constraints.

2.7. Role of injectors modern

The injector is one of the most important components of the system.

Its function is to transform the hydraulic energy of the fuel in a jet properly controlled.

The quality of the injection depends in particular on:
- of the geometry of the holes;
- the diameter of the holes;
- of the pressure;
- the opening time;
- from the opening speed;
- of the shape of the jet;
- of the position of the injector.

The progress in the design of the injectors, including fuel injectors multi-holes, and some technologies, piezoelectric, have helped to improve the mixture formation and the control of emissions.

2.8. The role of the calibration electronic

The direct injection modern requires a calibration is extremely accurate.

The calculator should determine a large amount of parameters.

The calibration must take into account:
- the speed of the engine;
- the load;
- the temperature;
- the pressure;
- the cold start;
- the acceleration;
- the deceleration;
- the protection of the engine;
- the emissions;
- the consumption;
- the performance.

Recent work emphasizes that the large number of calibration parameters is precisely one of the major challenges of engines GDI modern.

Thus, the advantage of direct injection cannot be dissociated from the development software of the engine control unit.

3. PRESENTATION, INTERPRETATION OF RESULTS AND DISCUSSION

3.1. Comparison between indirect injection and direct injection

Table 3.1 below gives us the comparison between indirect injection and direct injection.

Table 3.1. General comparison

Rep	Criterion	indirect Injection	direct Injection
1	Location of the injection	intake Duct	combustion Chamber
2	injection Pressure	is Generally the most low -	High
3	dosing Precision	Good	Very high
4	time Control of injection	is Limited	to Very specific
5	multiple Injection	Limited by system	adapted Very well
6	potential Yield	Good	High
7	specific Power	| Good	Potentially superior
8	Complexity	Moderate	High
9	Calibration electronic	Important	Very important
10	- Risk of particles GDI	Low	Potentially higher
11	- Cost of the system is	Usually lower than	Generally higher

3.2. Benefits for the automotive industry

The direct injection optimized electronically provides several benefits to industrial.

- **Potential reduction of consumption:** A better control of the fuel metering allows you to avoid some of the losses and improve performance.
- **Increase of the specific power:** manufacturers may search for a high power output with engine displacement capacity reduced.
- **Improvement of the control of the combustion process:** The electronic control allows you to adjust the fuel injection to the different operating conditions.
- **Potential reduction:** A strategy for the injection and properly calibrated can help to reduce certain emissions.
- **Adaptation to hybrid motors**: direct injection remains relevant in engines used as part of a hybrid powertrain.

3.3. Limitations and challenges

Direct injection, however, is not a perfect technology.

3.3.1. Particulate emissions

Engines GDI may present emissions of particles higher than engines with indirect injection in certain conditions. Systems such as particulate filters gasoline (GPF) can be used to meet the regulatory requirements.

3.3.2. Deposits on the injectors

The injectors operate under severe conditions of temperature and pressure.

The deposits can change the shape of the jet and disrupt the formation of the mixture, which can affect performance and emissions.

3.3.3. Complexity electronic

The technology requires:

- the sensors are accurate;
- a calculator is powerful;
- the software complex;
- the strategies of calibration sophisticated.

3.3.4. Cost

The high-pressure systems and their electronic components can increase the cost of manufacturing and maintenance.

3.4. Outlook

The current research focuses on several areas:

- optimization strategies injection;
- injection multiple;
- improvement of atomization;
- new injectors;
- control advanced combustion;
- use of oxygenated fuels;
- integration of artificial intelligence and predictive models;
- optimization in real-time;
- association with EGR;
- systems of post-treatment more effective.

A review published in 2026 says that the current research on engines, GDI focuses on the stability of combustion, emissions, strategies injection single or multiple, atomization, and the integration of technologies such as EGR and particulate filters gasoline.

3.5. Discussion

The analysis shows that the direct injection of optimized electronic control represents a major evolution of the car engine.

His interest lies not simply in the fact that inject the fuel directly into the combustion chamber. The real advantage comes from the ability to precisely control the injection process and to adapt it to the running snapshot of the engine.

The association between:
sensors + calculator + high-pressure injectors + strategy combustion

allows you to turn the power supply system in an intelligent system that is able to continually adapt the combustion.

This development, however, an important consequence: the more the system becomes efficient, the more complex it becomes.

The automotive industry must therefore find a balance between:
performance + consumption + emissions + reliability + cost.

The optimization of the direct injection should also be considered as a global process. The injector, high pressure pump, the control unit, the sensors, the software, the combustion chamber and the after-treatment system have to work together.

Recent advances show that the emissions of particulate engines GDI can be greatly reduced through the improvement of the strategies of injection, the design of injectors and particle filters gas.

4. CONCLUSION

The direct injection of optimized electronic order constitutes a real technological advantage for the automotive industry. It allows a master of much more precise combustion, thanks to the control of the amount of fuel, the pressure, the time of injection and, in some architectures, the number of injections per cycle.

This control helps to improve:

- the performance of the engine;
- the economy of fuel;
- the specific power;
- the couple;
- the quality of combustion;
- the emissions control.

However, the direct injection also presents a number of challenges, including emissions of particulates, deposits on the injectors, complexity, electronics, and cost.

The future of this technology will therefore depend on the ability of the automotive industry to develop simultaneously the hardware and software of control.

The direct injection must not be considered as a solution to isolation, but as part of a global architecture of propulsion smart, in which the sensors,

the ecu, injectors, combustion and after-treatment systems work in a coordinated manner.

In this perspective, the electronic control is the real factor optimization: it transforms the direct injection of a simple mechanical system to power in a dynamic system, able to adapt in real time to the needs of the engine.

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