

THE LATEST ACHIEVEMENTS IN GASOLINE AND DIESEL INJECTION TECHNOLOGY FOR THE INTERNAL COMBUSTION ENGINES

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Abstract

The paper presents an overview of the latest achievements in gasoline and diesel injection technology. It is already clear that in 20 years' time the internal combustion engine will still be the drive of choice for the car. Indeed, it still offers a great deal of development potential.

Thanks to sophisticated solenoid and piezo-injectors, engineers can now build smaller engines without sacrificing performance and torque. They refer to this as downsizing. Less engine displacement and fewer cylinders ensure reduced friction losses and therefore greater efficiency. With the same levels of torque, 25 percent less engine displacement cuts fuel consumption by around ten percent. And lower consumption means less CO₂. Gasoline and diesel direct injection makes engines even more economical and eco-friendly.

Gasoline direct injection, combustion strategies for stratified-charge operation, GDI injectors, solenoid GDI injectors, piezo GDI injectors, Common Rail Injectors, Common-Rail injectors with piezo actuator, Common-Rail injectors for commercial vehicles, weaknesses of modern high pressure common-rail injectors, multiple injections, Hydrogen Supply Systems, technical requirements for H₂ injectors, control range and duration of injection pulse are presented in the paper.

Keywords: *direct injection, combustion, diesel, gasoline, common rail, di-motronic*

1. Introduction

For the next 20 years, the internal combustion engine will remain the automotive drive of choice. Using the technology available today, a car equipped with an internal combustion engine can drive 40 times further than electric vehicles per kilogram of energy stored. Compared to standard engine, modern engine systems are considerably more fuel efficient: a gasoline engine with direct injection and certain features of downsizing consumes 15% less fuel. In contrast, a conventional diesel engine with common-rail injection consumes 30% less fuel, the same amount as a gasoline hybrid.

Worldwide, just under two-thirds of cars sold today have a gasoline engine with manifold injection. Solely with direct fuel injection and a slightly downsized engine, it is possible to reduce fuel consumption by a good 15%, with a corresponding reduction in CO₂ emissions. Several automobile manufacturers have taken the lead in this field, especially with high-volume gasoline-powered models that employ the direct injection system. In Europe, for example, this system has been adopted by Volkswagen and BMW. In the U.S., Ford uses it in its "EcoBoost program" for 6-cylinder engines. And in Asia, it is found in Suzuki K-cars with 0.66-liter, 3-cylinder engines.

In addition gasoline direct injection allows the first series application of the new HCCI (homogeneous charge compression ignition) combustion process for the gasoline engine. The improved efficiency provided by this process, especially in the partial load range, could reduce gasoline consumption by a further two to three percentage points.

To improve the efficiency of the diesel engine, the 2500 bar piezo multihole Common Rail injectors which can release up to 8 injections per cycle in accordance with the injection-map, already had been launched into the market.

At last increasing significance is being attached to hydrogen as an alternative fuel for internal

combustion engines. It seems to be clear, that in next 50 years hydrogen as a fuel will be replacing other fuels including gasoline, diesel, and ethanol. These advantages include potential of near zero emissions of the regulated emissions of CO, NO_x, and HC while simultaneously eliminating CO₂ emissions. Hydrogen's combustion properties enable the development of an engine that would meet all current and future emissions standards at a price comparable to current engines with less costly aftertreatment devices. In addition because of cold start capability the H₂-ICE (H₂ Internal Combustion Engine) hydrogen engine are more attractive for automotive industry than fuel cells.

2. Gasoline Direct Injection

Direct Injection Gasoline Engine is investigated to improve the engine performance, fuel economy, avoid engine knocks and reduce emission of harmful gases causing environmental pollutions. The Direct Injection Gasoline Engine can be realized as stratified charge combustion and a homogeneous combustion. In locally stratified charge combustion method, stoichiometric combustible mixture is formed around the spark plug in order to burn an ultra lean mixture. It is possible at lower engine speed and torque range. The engine runs with a heavily stratified cylinder charge and high level of excess air in order to achieve the lowest fuel consumption. The ideal state is to achieve two zones, the stoichiometric air/fuel mixture cloud is situated at the spark plug, and an insulating layer of air and residual exhaust gas is embedded in a second zone. As engine torque and also injected fuel quantity increase, the stratified charge cloud becomes increasingly richer, which has an influence on exhaust emission, particularly with regard to soot. Therefore, the engine starts to operate with a homogeneous cylinder charge in this higher torque range. Fuel is injected during the intake stroke in order to ensure that fuel and air are mixed. This operating mode must also be set at high engine speeds (> 3000 rpm), as the charge stratification and proper transport of the mixture to the spark plug can no longer be maintained. This is because turbulence is too high and there is not enough time to inject the required quantity of fuel.

2.1. Combustion strategies for stratified-charge operation

Wall-directed combustion strategy- fuel is injected into combustion chamber from the side (Fig.1). A recess in the piston crown deflects the fuel spray in the direction of the spark plug. The disadvantage of this system is that fuel condenses on the wall, which increases HC emissions.

Air- directed combustion strategy- works in exactly the same way as a wall-directed system. The main difference is that the fuel cloud doesn't interact directly with the piston recess. Instead the charge cloud moves on a cushion of air, what solves the problem of fuel condensing on the piston recess.

Jet-directed combustion strategy- is visually different from the above mentioned processes in that the injector is installed at top center and injects vertically down into the combustion chamber (Fig.2). The spark plug is located immediately next to the injector. The fuel spray is not deflected, it is ignited immediately after injection, the mixture formation is very short, what requires an even higher fuel pressure. This combustion system can eliminate the disadvantages of fuel condensing on the piston recess and cylinder wall as well as air flow dependency, and flow restriction at low loads. Therefore it has the greatest potential for fuel savings and performance. Nevertheless, the short mixture formation time is a huge challenge for fuel injectors.

3. GDI Injectors

The design of the fuel injector plays a key role in the performance of GDI engines. Generally, there are three types of fuel injector concepts for GDI engines, namely, swirl-type, slit-type, and multi-hole. Each concept has its own advantages. However, the multi-hole injectors are more

promising because they offer the long sought spray pattern tailoring flexibility and reduced penetration. The multi-hole injectors are available in a solenoid and piezo technology.



Fig. 1. Wall-directed combustion system



Fig. 2. Jet-directed combustion system

3.1. Solenoid GDI injectors

The latest generation of GDI solenoid injectors (Fig.3) ensures well-defined mixture of fuel and air in a certain area of the combustion chamber through fuel atomization. Dependent on the required operating condition, the fuel is concentrated (stratified) in the area around the spark plug or is atomized evenly throughout the combustion chamber (homogeneous distribution).



Fig. 3. Second generation of solenoid GDI injectors HDEV5 from Bosch

The second generation of solenoid GDI injectors ensures:

- Reduced emissions thanks to no pre-jet, multi-hole technology, which improves spray preparation in terms of evaporation behaviour.
- Potential for consumption reduction, because the High Pressure Injector offers high design freedom through almost free alignment of up to 7 single beams (Fig.4). The engine development engineer converts this into optimized control times and pulse widths.

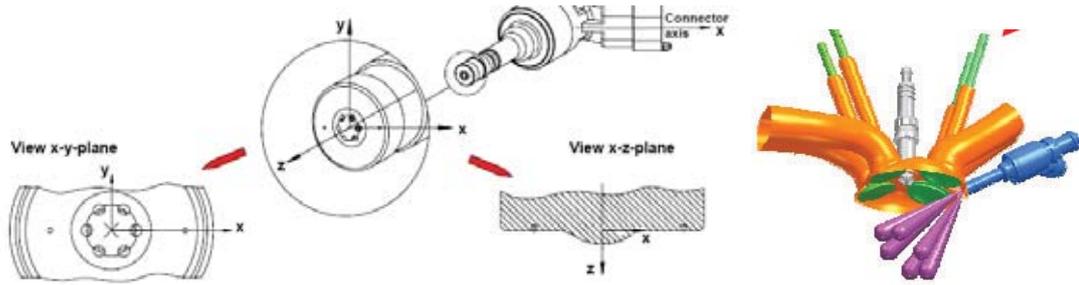


Fig. 4. The injection nozzle is available in a symmetrical and nonsymmetrical design, with number of holes from 4 up to 7

Easy assembly is in both for central and side installation. Adjustment is to engine-specific mounting conditions. The modular design of the GDI Injector allows for variations as to the hydraulic connection (O-ring, screw type connector) or the length of the Injector.

Its flexibility regarding spray shape (Fig. 5) and flow rate qualifies the High Pressure Injector for various engine types. Today the Injector is used worldwide in the 1.0 l 3-cylinder as well as in the V8 with turbocharging both for fuel consumption (e. g. downsizing) and fun-to-drive concepts (e. g. in combination with turbo-charging). At the same time the High Pressure Injector supports different engine operating points – from high-pressure start with catalyst heating and multiple injection to homogeneous full load.



Fig. 5. The spray shapes of the GDI solenoid injectors

3.2. Piezo GDI injectors

The main difference between solenoid and piezo injectors is that the piezo element is smaller than the solenoid one. Consequently, there is no need for a long plunger, the mass which moves during opening and closure is reduced, and the needle accelerates more rapidly, allowing faster injection operation (Tab. 1). Shorter response times, i.e. the times between the energizing of the injector and the start of injections a one of the major benefits of piezo-driven injectors compared to solenoid injectors.

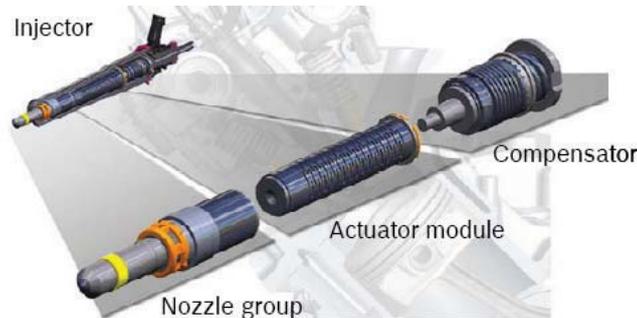


Fig. 6. Main modules of the GDI piezo injector

Tab. 1. Technical data GDI Piezo Injector HDEV4 from Bosch

System pressure	200 bar
Droplet size SMD	10-15 μm
Needle lift	35 μm
Lift range	> 10-35 μm
Multiple injection	up to 3 times
Opening/ Closing time	180 μs /200 μs
Pause time	< 50 μs
Flow rate	0.75-150 $\text{mm}^3/\text{Inj.}$
Leakage	<2.5 mm^3/min @ 20 MPa
Voltage	130 V
Weight	260 g

HDEV4 is a high speed Piezo actuator injector for gasoline fuel with variable needle lift. The outward opening nozzle generates a very stable spray (Fig.7) with a high deposit resistance. The injector covers a high flow range where it shows a high linearity with regard to q_{dyn} (Fig. 8). Its possible fast and precise multiple injections offer new potentialities to shape the injection cycle.

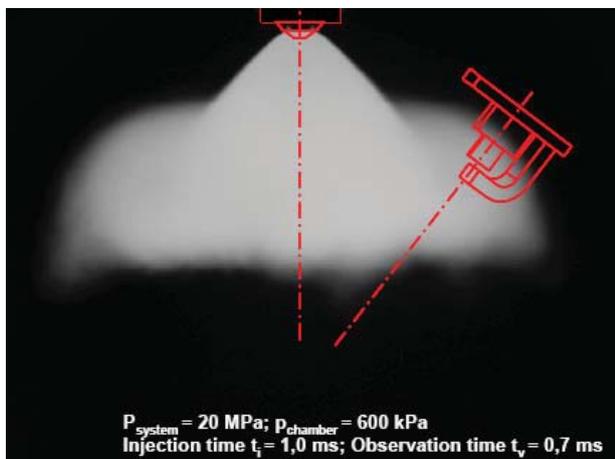


Fig. 7. Spray shape of the GDI piezo-injector



Fig. 8. Dynamic q_{dyn} characteristic

4. Common Rail Injectors

The very first development projects were started in the late 1980s to develop a fuel system for the future diesel powered passenger car. It was apparent that, due to the clear advantage in fuel economy and power density, the future cars would utilize direct injection combustion process. In the common rail system, fuel is distributed to the injectors from a high pressure accumulator, called the rail (Fig.9). The rail is fed by a high pressure fuel pump. The pressure in the rail, as well as the start and end of the injection in each cylinder are electronically controlled. Advantages of the common rail system include flexibility in controlling both the injection timing and injection rate. Stable pilot injections which can be delivered by the common rail have proven to lower the engine noise and the NOx emissions.



Fig. 9. Modern common-rail injection system

4.1. Common-Rail injectors with piezo actuator

The latest injector development in the 3rd generation works with a piezo-actuator instead of solenoid valve (Tab. 2). The piezo actuator is significantly faster than the solenoid. For instance piezo injector has $60\mu\text{s}$ shorter response times than solenoid. However, this requires a modification of the design in order to be able to utilize the advantages of the piezo-feature.

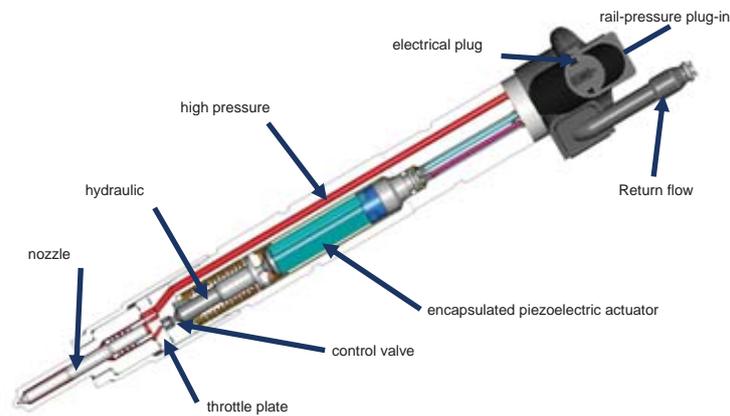


Fig. 10. Design of the common-rail piezo injector

The nozzle needle is directly controlled hydraulically by the actuator so that there is no mechanical connection between actuator and nozzle needle (Fig. 10). This approach eliminates all friction as well as any elastic deformation of the connection elements. As the nozzle needle in the piezo-injector is now much lighter (approx 4 g against 12 g) and the leak-fuel quantity at the actuator has been dramatically reduced so that smaller high-pressure pumps can be used.

Tab. 2. Comparison CRI3.x (Piezo) - CRI2.2/2.3 (Solenoid) from Bosch

Feature	CRI2.2	CRI2.5	CRI3.0	CRI3.2	CRI3.3
Pressure capability	250...1600 bar	250...1800 bar	230...1600 bar	230...1800 bar	230...2000 bar
Leakage	2.5 l/h	?	0 l/h	0 l/h	0 l/h
Needle speed _{max}	V_{open} : 0.8 m/s v_{close} : 0.8 m/s	V_{open} : 0.8 m/s v_{close} : 0.8 m/s	V_{open} : 1 m/s v_{close} : 1.2 m/s	V_{open} : 1.2 m/s v_{close} : 1.3 m/s	V_{open} : 1.2 m/s v_{close} : 1.3 m/s
Number of injections	≤ 4	≤ 7	≤ 8	≤ 8	≤ 8

Further series of advantages:

- the structural space is smaller i.e. more compact,
- the weight is reduced by almost half,
- several injections per injection cycle can be affected, e.g. two pilot injections, one main and two post-injections (Fig. 11),
- the injected fuel quantities of the pilot-injections can be reduced,
- the intervals between injections can be shortened.

4.2. Common-Rail injectors for commercial vehicles.

Modern common rail injection systems can deliver fuel at pressures up to 2000 bar and it is likely that future developments will result in even higher pressures especially in case of injectors for commercial vehicles (Fig. 12). The fuel pressure in 4th generation of injectors Bosch CRIN 4.2 (Fig. 14) for commercial vehicles can reach even 2500 bar due to 2-stage pressure amplifier inside (Fig. 15) of the injector, in addition injector is equipped with 2 solenoid valves for injection rate shaping.

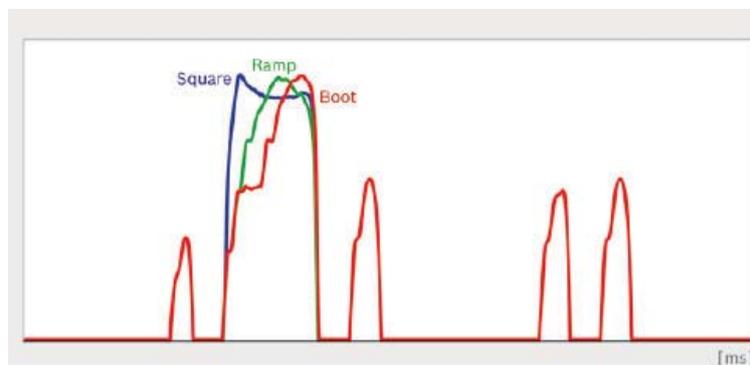


Fig. 11. Injection rate shape of CR piezo-injectors

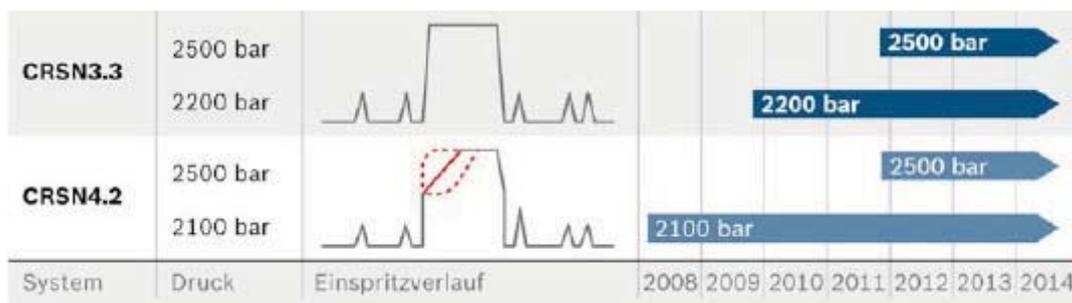


Fig. 12. Further system pressure development CR systems for commercial vehicles

4.3. Weaknesses of modern high pressure common-rail injectors

4.3.1. Cavitation

It is obvious, that even more system pressure we reach, the formation of a diesel spray can be affected by cavitation in the injector orifice or even in the sac (Fig. 13.). The flow in the orifice is at several hundred meters per second and highly turbulent, with Reynolds number of 5000. Cavitation contributes to increased break-up of the diesel spray and to wider spray angle. Furthermore, the cavitation may cause large, cyclic, disturbances in the existing jet. The cavitation number decreases with increased inlet pressure, or decreased outlet pressure.

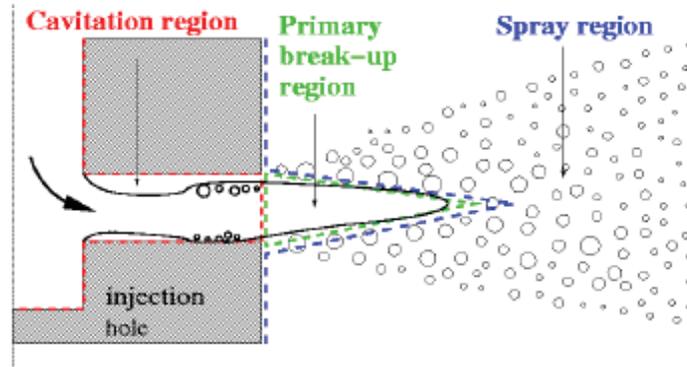


Fig. 13. Cavitation in the injector orifice

4.3.2. Liquid penetration

If liquid penetration is too long it can lead to increased emission if impinges into piston bowl surface, the liquid length is linearly proportional to the orifice diameter. The injection pressure had, however insignificant effect on the liquid length.

4.3.3. Multiple injections

Splitting the injection in more than one part can give a significant effect on the mixing and evaporation process. Due to the compressibility of fluids, rapidly opening and closing a valve in hydraulic system under high pressure, e.g. common rail injector creates pressure waves that make the pressure fluctuate in the system. The opening and closing of the injector, i.e. the movement of the needle, is also depended on the pressure in the injection system. So, not only the flow, but also the mechanical behaviour of the injector, can be disturbed by an earlier injection. The pressure fluctuations also made the needle position oscillate after the end of injection for both piezo and solenoid injectors.



Fig. 14. 4th generation of injectors for commercial vehicles Bosch CRIN 4.2



Fig. 15. The main modules of CRIN 4.2, actuator, hydraulic amplifier and nozzle from left, respectively

5. Hydrogen Supply Systems

More than a century, hydrocarbon fuels have played a leading role in propulsion and power generation. In recent years, declining oil reserves and increased fuel prices have, together with increased awareness of the environmental impacts of burning hydrocarbon fuels, led to an interest in alternatives to fossil fuel-based propulsion and power generation. One such alternative is to use hydrogen as an energy carrier and to extract energy using a fuel cell or a modified internal combustion engine. Hydrogen possesses some features that make it attractive for use as a fuel in internal combustion engines, enabling fast, close to constant volume combustion, high combustion efficiency and low emissions. There are several works under development utilizing hydrogen for vehicle technologies carried out by automotive manufacturers. For example, BMW Group has applied hydrogen to their passenger vehicle V12 6 L engine with a power of 155 kW and torque of 340 Nm (Fig. 16). Hydrogen is stored in liquid state in an insulated tank of volume 170 L, which allows driving range of nearly 300 km.

5.1. Technical requirements for H₂ injectors

At the beginning the H₂ICE (Hydrogen Internal Combustion Engine) were equipped with the port fuel injection systems. Such projects had been performed i.e. by MAN and BMW. In 1982 BMW launched H₂ engine with mechanical injection system and in 1992 the electronic port fuel injection system was presented, in which the injectors had large orifice diameter.



Fig. 16. Solenoid actuated inward opening ported valve plate injectors integrated into air manifold of BMW Hydrogen 7 car; injector characteristics: Flow area: 7 mm², Δp_{max} : 5 bar.

5.1.1. Orifice diameter

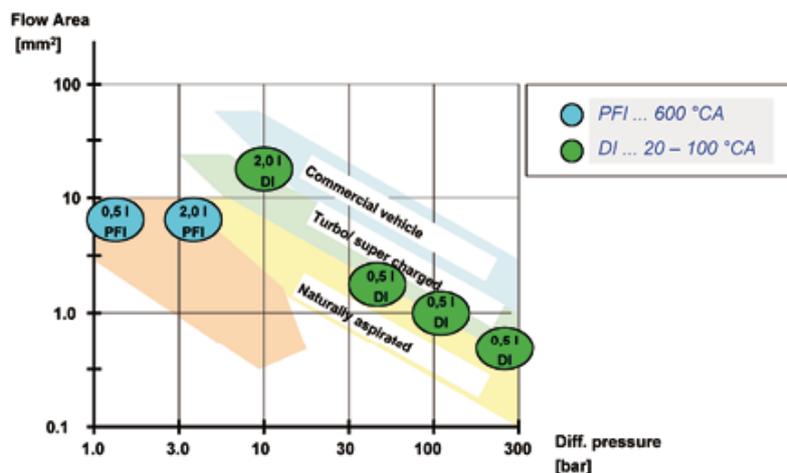


Fig. 17. Required equivalent flow area for 0.5 l/cylinder and 2.0 l/cylinder engines as function of fuel supply pressure and fuelling method (PFI – Ported Fuel Injection – injection duration max. 60° CA, DI – Direct Injection – injection duration max. 20° CA (late injection) and 100° CA (early injection))

5.1.2. Control range and duration of injection pulse

Tab. 3. Required control range and shortest duration for various fuel admission strategies for car engines

Operating mode	$T_{\max}:T_{\min}$	T_{\min}
PFI constant inlet pressure	20:1	1 ms
PFI pressure control 1:2	10:1	2 ms
PFI cryogenic	30:1	0.5 ms
DI early injection (100°CA)	15:1	0.4 ms
DI late injection (20°CA)	15:1	0.2 ms
DI multiple injection	10:1	0.1 ms

5.1.3. Injection precision

The fuel must be injected in an exact quantity, the maximum tolerance is 2%. In comparison with any others fuels like gasoline or diesel, the hydrogen required extremely narrow tolerance.

5.1.4. Temperature

Especially the design of DI injectors in order to the high temperatures in combustion chamber is very critical. The injector nozzle in cylinder during engine operation can reach temperature from 300 up to 400 °C. A proper heat exchange in the cylinder head is extremely important to maintain low temperature of the injector in order to avoid auto ignition of hydrogen by too hot nozzle and to protect Nometall-Components, like all sealing parts made of PTFE (Polytetrafluorethylen). In addition the temperature in cylinder for hydrogen–air is higher than for gasoline–air charge, because of cooling reffect from the gasoline fuel vaporization.

5.1.5. Hydrogen

In compare to natural gas, hydrogen contain no humidity and lubricants, it means that the micro movements between sealing parts of the injectors have to be eliminated. There is no place for lateral movements between sealing parts and moving parts of the injectors, furthermore the guided elements must be made of self-lubricant materials.

5.2. Type of Injectors

H₂ injectors are generally sorted as a port and direct injectors. Nowadays the latest H₂ICE research engines are equipped with H₂ DI injectors. Low pressure DI Injectors can deliver fuel at 10 bar and the orifice diameter is about 13 mm². (Fig. 18) and high pressure injectors operate at 100 bar and 1 mm² orifice diameter (Fig. 19).

Numerous of experiments and simulations (Fig. 20) have investigated the use of hydrogen in spark ignition (SI) and compression ignition (CI) engines, and the feasibility of hydrogen as a fuel in such engines is well established. The flame speed of hydrogen is higher and hydrogen allows operation at significantly higher excess air ratios than conventional hydrocarbon fuels. This enables extended lean burn operation of the engine, potentially leading to a drastic reduction of NO_x emissions.



Fig. 18. Solenoid actuated, outward opening multi ported valve plate injector for low pressure (early injection) DI operation of MAN urban transportation



Fig. 19. HyICE High pressure (late injection) DI: solenoid actuated needle injector; injector characteristics; flow area: 1 mm², p_{cyl.max}: 180 bar, p_{H2max}: 250 bar

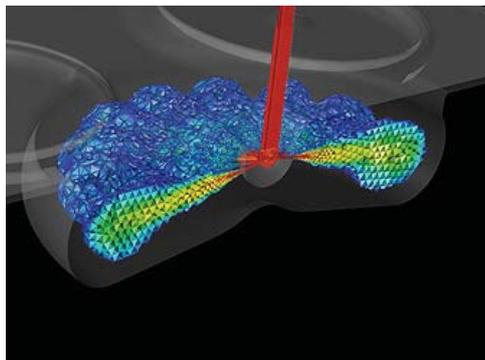


Fig. 20. 3D-CFD Simulation of DI high pressure injection

6. Conclusions

The design of the fuel feeding systems plays a key role in the performance of internal combustion engines. Latest achievements in SI and CI engines development have been done with the great contribution of modern injection systems. Furthermore the latest generation of injection systems is designed not only for conventional fuels but also for alternative, like ethanol, biodiesel or natural gas (CNG) and hydrogen (H₂).

In addition to combustion chamber design the modern high pressure injectors due to very precise injection metering allows to use the HCCI technology, which replace this wasteful

combustion method, at least in the partial engine load range. This new combustion process makes it possible to meet future nitrogen oxide limits in the engine's partial-load range without costly exhaust after-treatment systems.

The more precise control of the injector, and the finer the atomization that can be achieved with the injector nozzle, the better the mixture formation, and the lower emissions result from combustion in gasoline, diesel or hydrogen engines.

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