



Development of High-Pressure Injectors for Gas and Hydrogen

Gas-hydrogen blends as well as pure hydrogen offer great potential for large engines, as they can replace carbon-based fuels and achieve high energy efficiency. One of the biggest obstacles to the commercialization of these fuels is the lack of injection systems for gas and hydrogen. ITAZ GmbH and DUAP AG have jointly developed such injectors, with special consideration of short injection times for load quantities and idle volumes.

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The increase in the concentration of CO₂ in the atmosphere is a major factor in global warming. The world's steadily increasing energy demand is still being met mainly by fossil fuels [1].

Driven by legal, social and economic factors, the further development and improvement of internal combustion engines will continue. International legislation on exhaust gases and pollutants, fuel types and fuel consumption will also be adapted in view of global CO₂ emissions and limited fossil resources. One focus is on optimizing the power density of engines for heavy-duty and long-haul transport on land and water; another is on the economic efficiency in the operation

of CO₂-neutral propulsion and power generation systems.

REQUIREMENTS FOR GAS INJECTORS

The fuel supply chain, injection strategy and injection equipment have a strong impact on combustion, emissions and overall engine performance, **FIGURE 1**. Based on many years of experience in the development and manufacturing of mechanical and electronic injection systems, ITAZ and DUAP defined a detailed specification sheet.

The design, manufacturing and application of natural gas engines has long been well understood. This is not the

case with direct hydrogen technology in combustion engines. Nevertheless, the combustion principles for hydrogen direct injection systems follows similar principles. The combustion strategy requires the control of a homogeneous air-fuel mixture, a safe ignition source and efficient heat dissipation during the combustion cycle.

In contrast to intake manifold injection, direct injection (DI) has almost no effect on volumetric efficiency loss after the intake valve has been closed. In addition, the direct injection has no fuel slip into the intake manifold. This eliminates the possibility of misfires in the intake air duct.

PROPERTIES OF INJECTORS FOR DIRECT INJECTION

Most DI fuel injectors are controlled by direct activation of the needle or the activation by a pilot valve. Directly controlled injectors are simpler in design and in most cases, the stroke and seat diameter of the nozzle defines the force and stroke of the magnet and thus the diameter and electrical power for it. Above a certain physical limit, the magnet can be very large, which also unfavorable effects the dynamics. Gas engines require large volumes of gas, so that large nozzle openings and flow cross-sections have to be switched. The described injector is piloted with a 3/2 valve. The solenoid is small in this case, since only the pilot valve needs to be controlled with constant forces, regardless of the system pressure.

The DI injector is driven by the fuel gas. Compared to hydraulically controlled injectors, the gases show a very stable control function. The returned control gas leakage in the intake manifold is very low, and will get dispersed in the next combustion cycle. The low

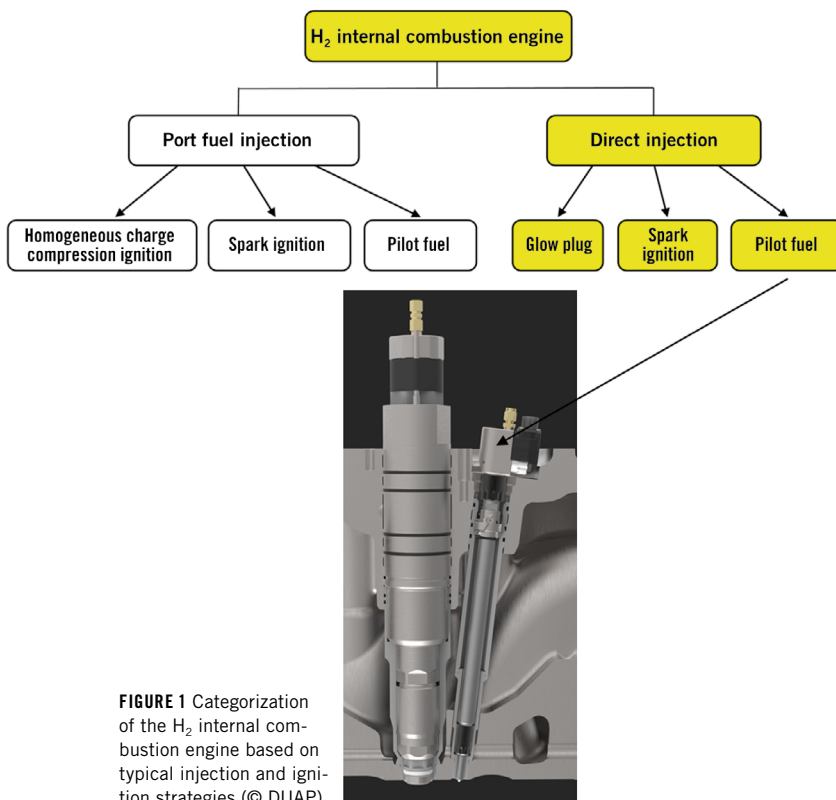


FIGURE 1 Categorization of the H₂ internal combustion engine based on typical injection and ignition strategies (© DUAP)

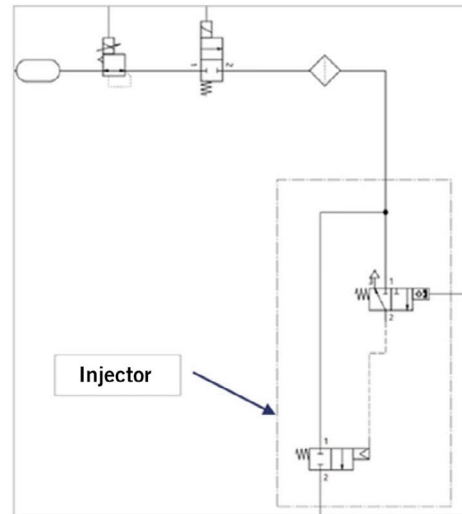
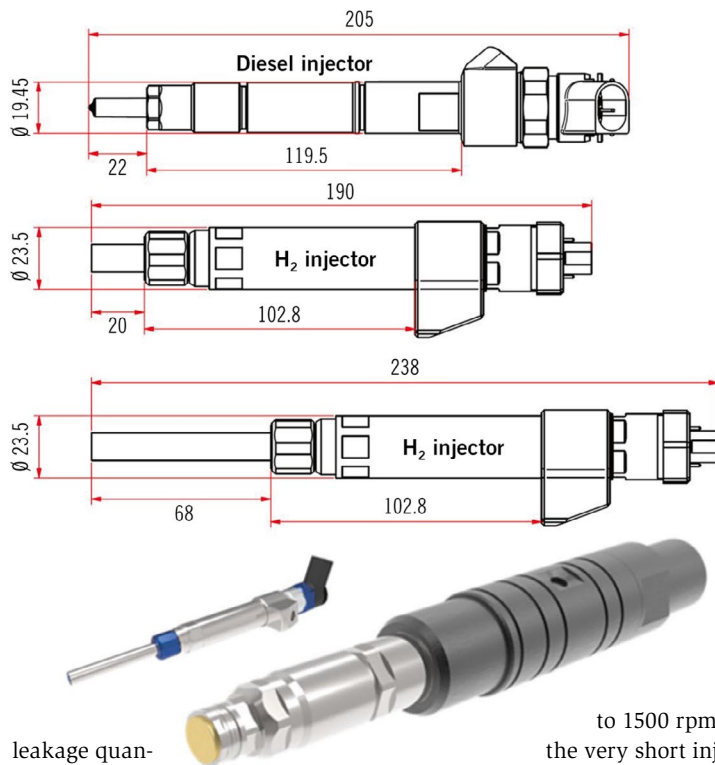


FIGURE 2 Possible injector dimensions and functional pattern (© ITAZ, DUAP)

leakage quantity amount of around 1 % of the injection quantity will reduce the risk of unwanted burns in the manifold.

The DI injectors are defined for low-pressure applications between 10 and 50 bar. This pressure is used to empty the gas tanks to a possible low value. By adjusting the injector, system pressures of up to 300 bar are currently possible.

INJECTOR CONTROL

The actuator is controlled by a classic amplifier controller with a peak-and-hold strategy. This opens the valve and drives the needle piston. Small pneumatic volumes allow good dynamics. As soon as the needle begins to open, the injection event begins and gas is injected into the combustion chamber. Depending on the cylinder size, the injection stops as soon as the defined quantity has been blown in. The pilot valve closes and the needle is pushed back to the closing position. Since the needle is pressure-balanced, the closing forces inside the injector are always the same.

The described injector has a defined full load injection mass of 200 mg per injection, the idle quantity is about 10 mg. These values correspond with cylinder volumes of 3-5 l. With 50 bar system pressure, the injection takes up about 5-6 ms. With engine speeds of up

to 1500 rpm and due to the very short injection times needed, there is significantly more time for the homogenization process. From 15 mg full load quantity (passenger car) up to large engines with full load of 5000 mg or more are possible, **FIGURE 2**. This works for any combustion gas, also for hydrogen.

SIMULATION AND RESULTS FOR INJECTION

The injector function was designed using 1D simulation. In order to

simulate the injection quantity, the injector was defined with 60 individual parameters in order to achieve the desired results for both the rate of injection trace and the injection quantity. On the functional test bench, the detailed calculations results have been confirmed with high accuracy.

The smaller the pressure drop in the injector, the better the efficiency and the better the maximum use of the hydrogen tank volume. This leads to a higher operating hours or distance and a higher economical use for the operator. Since gases are compressible, thermodynamics must

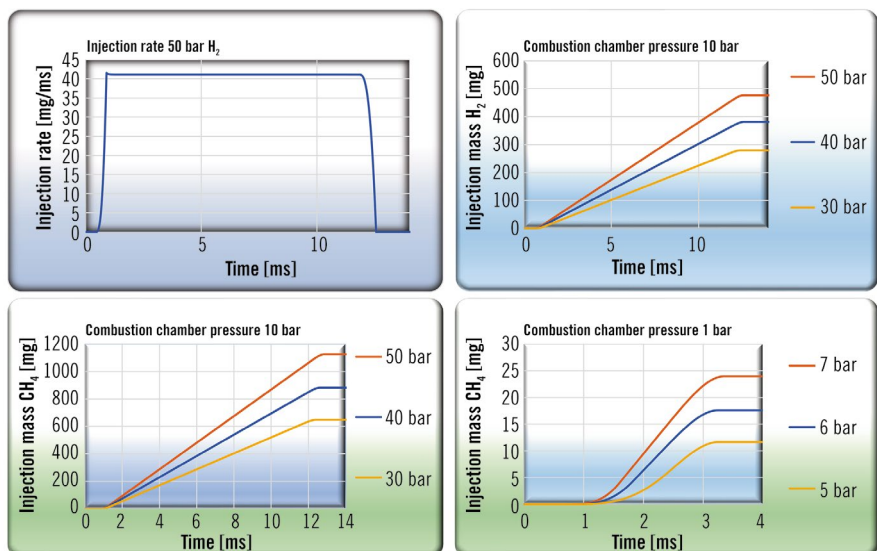


FIGURE 3 Injection rate and quantity for full load and idle (© ITAZ)

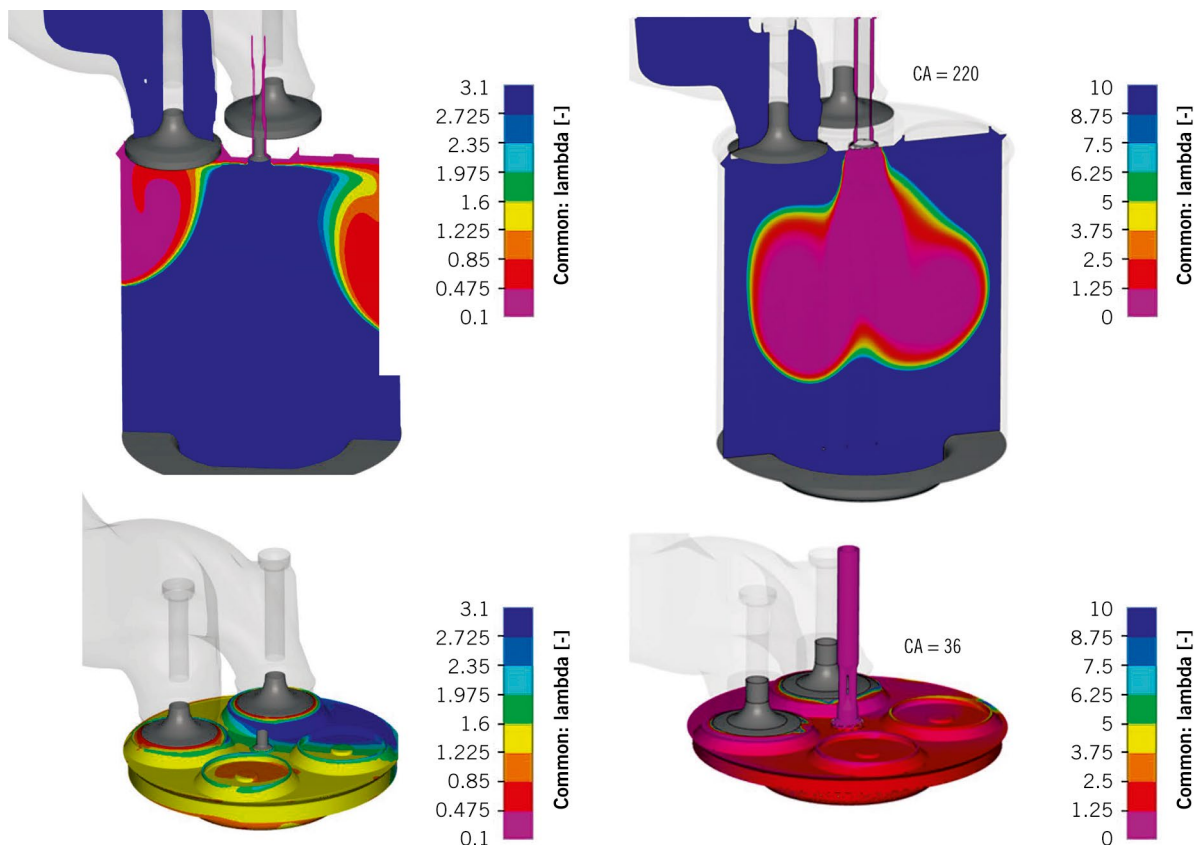


FIGURE 4 Simulation Lambda for full load, in the injection phase and at the upper dead center (© ITAZ)

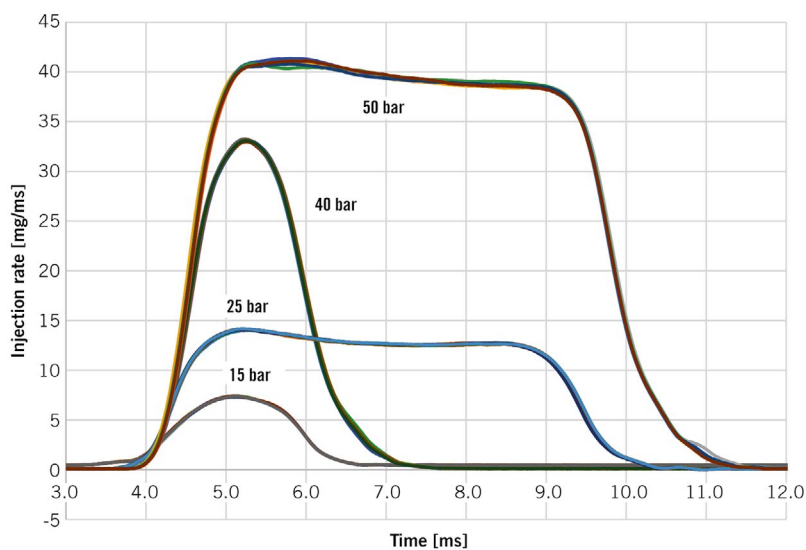


FIGURE 5 Injection rates at different system pressures (© ITAZ)

be taken into account for the correct calculation. Each pressure point is considered thermodynamically to ensure the correct overall simulation values.

A very important result, for the injection, is the rate of injection trace; calculated with the 1D simulation tool,

FIGURE 3. The graph shows the characteristics of the injector and gives the engine designer the information needed for the injection event, mass flow and timing, including starting and closing behavior. The injection quantity indicates the amount of gas injected over time as a

characteristic for the injector. This is another result of the 1D simulation. The target von 200 mg for full load can be achieved at 50 bar in approximately 4.5 ms.

Other gases such as CH_4 or a mixture of H_2 and CH_4 are also possible and show similar behavior. The pilot control for the injector works in the same way, even with different gases. The idle quantity for the 4-litre cylinder size is 10 mg per stroke. The amount can be injected in ballistic mode (see 6 and 7bar) or with the fully opened nozzle (see 5bar). In the case of hydrogen gas, the characteristic curves are comparable.

CFD SIMULATION OF THE AIR GAS MIXTURE

Another important step is the mixture control strategy. Depending on the lambda value allocation in the combustion chamber, the efficiency and NO_x value of the engine are influenced. In a first step, two versions were compared, **FIGURE 4.** One is a classic external opening nozzle with 120° seat angle, flush with the cylinder head. The second

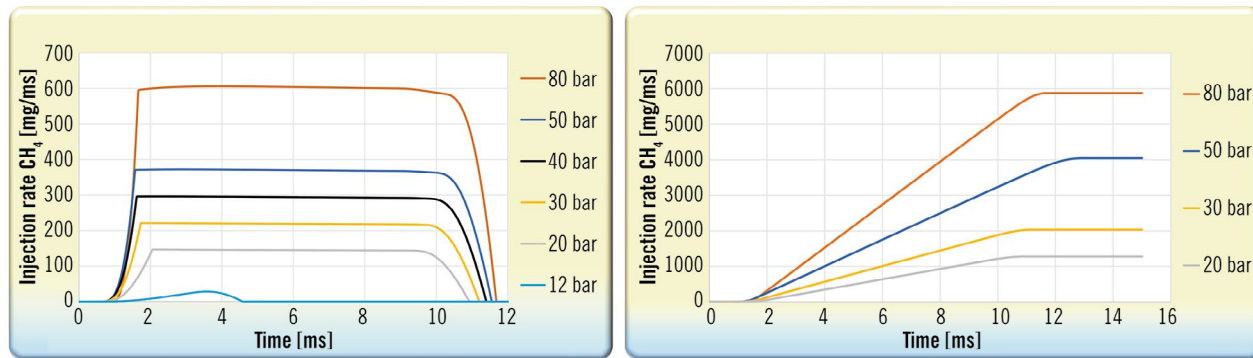


FIGURE 6 Injection rate and quantity of large injector (© ITAZ)

version has a cylindrical guide up to the combustion chamber. The simulation is carried out with full load quantity of 200 mg and 3.5 bar turbocharger pressure. It is noticeable that version one with 120° seat angle has a mixture distribution close to the cylinder head and cylinder walls and - compared to version two with deep injection centered in the combustion chamber - a worse lambda distribution to the potential ignition timing. The concept is able to support a combustion development due to its flexibility in nozzle seat design and of the gas jet guidance.

The above approach was an important step in understanding the overall impact on gas jet conduction. The optimization work is carried out in teamwork with the customers and thermodynamic engineers of the engine developers.

FUNCTIONAL RESULTS

In order to confirm the simulation results, functional measurements were carried out, in the beginning with helium, **FIGURE 5**. The following graphs show 4 different load cycles at room temperature, one idle load at 15 bar system pressure, two medium loads at 25 bar, 40 bar and one full load at 50 bar.

The 8 and 13 injections per load point show a very stable initial rating. On average, a Six-sigma value of about 2.5 % was calculated, the relative measurements are about 1.2 %.

INJECTOR FOR LARGE ENGINES

On the basis described above, a DI injector for large engines was created by

DUAP and ITAZ. The maximum full-load injection quantity for hydrogen is about 1000 mg, or 4000 mg for CH₄. The cylinder power is 450 kW at 750 rpm. The minimum quantity capability is 52 mg hydrogen, respective 200 mg CH₄.

Due to the lower density of gaseous fuels, DI gas injectors must be equipped with appropriate nozzle cross-sections and switching valves. An outward-opening nozzle with a seat diameter of 25 mm was chosen. Depending on the application, the needle stroke is 750 µm to 1000 µm.

The dimensions of the injector are 475 mm overall length, 75 mm outer diameter and 25 mm valve diameter. The injector has a mass of 22 kg.

The characteristics of the injector are shown with the injection rate, **FIGURE 6**. The curves at different pressures show the rate curve over the blow-in time. This can be adjusted as required. The calculation of the quantity curves was carried out via a 1D simulation. The required 4000 mg CH₄ are injected, at 50 bar, after about 11 ms opening time of the nozzle. At 80 bar the blow-in time is approx. 6.5 ms. This can be advantageous for homogenizing the gas with the air. However, the higher pressures are more energy intensive in compression, and it is necessary to weigh up the balance against the overall efficiency.

The diagram shows the characteristics of the injector and gives the engine designer the necessary information for the injection event, the mass flow and the timing, including the start and closing behavior. The smallest quantities were achieved with smaller pressures. At 12 bar, 52 mg injection quantity is calculated in the specific application. This is already very low and probably

significantly more gas is needed for a stable idling. The graph shows the smallest quantity capability for the injection rate.

Mixture formation is absolutely crucial for optimum combustion performance and energy conversion. The injection position, the air loading system, the air charge dynamics, the nozzle shape and the injection jet guidance must be coordinated. In large, medium-speed and sometimes high-speed combustion engines, ignition jet systems with diesel or biodiesel are increasingly becoming popular for igniting gas mixtures. This has the advantage that higher compression ratios can be driven. The ignition window for diesel ignition jet engines is in a very broad fuel air ratio. Operation up to seven times the excess air is theoretically possible.

OUTLOOK

In view of the market development for hydrogen and other gas engines such as natural gas or ammonia, the injector for direct injection has a future. The presented injector concept is characterized by a high degree of flexibility, as the technology can be applied to very small applications such as a passenger car, medium-sized engines for trucks, heavy commercial vehicles or off-road vehicles such as marine engines. The basic technology is modular and can be used for various customer specifications. The pressure range and injection volume can also be adjusted.

REFERENCE

- [1] Hoffmann, G.; Dober, G.; Piock, W.: Borg Warners injection system for natural gas and hydrogen. 30. Aachener Kolloquium, 2021

