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Hydraulically actuated hydrogen DI-injector

Fuel Injection & Gas Admission and Engine Components

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ABSTRACT

One of the main challenges today and in the next decades is undoubtedly the decarbonization in the energy sector. While electrification of heating and cooling in buildings and important transportation sectors is already possible, other sectors will continue to benefit from the advantages of IC (internal combustion) engines and gas turbines for many years to come. Large high-power IC-engines, employed in different applications such as mining, commercial ships and electric power generation, will remain a pillar in the future.

The energy conveyed by solar radiation to the earth is more than 5,000 times higher than the current human energy consumption, making it evident that, in the long term, enough renewable electricity could be provided by photovoltaics and wind power. However, the temporal, highly variable character of such sources makes it necessary to transform the green electricity into green fuels, such as hydrogen (H2), methane (CH4), methanol, ammonia or DME (dimethyl ether), which will coexist with coal and crude-oil fuels in the market.

In internal combustion engines, the most thermodynamically efficient process is the diesel cycle, which is mainly applied to diesel fuel but can also be adapted for alternative green fuels. For the injection of such fuels at various pressures (relatively low pressures for H2 and CH4 and higher pressures for liquid green fuels such as methanol, ammonia and DME), an injector with the same basic actuation concept is advantageous. This paper presents the concept of such an injector, which has been successfully developed by Ganser CRS.

Diesel common rail injectors have been developed and constantly improved over the last decades. For hydrogen injectors, this development path is still in earlier stages. Thus, it seems reasonable to extend the knowledge of hydrogen injection on a smaller scale first.

For this purpose, Ganser CRS has developed a new medium-pressure DI (direct injection) hydrogen injector for a single-cylinder test engine with a 1-liter displacement, by using state-of-the-art simulation tools as well as different testing methods. This new hydrogen injector will contribute to identifying the challenges of hydrogen injection and its impact on engine operation, performance and emissions.

1 INTRODUCTION

The worldwide goal of greenhouse gases reduction, climate-neutral power generation and green energy pushes many industries to rethink their technologies and processes. Among others, engine manufacturers aim to replace fossil fuels with alternative fuels which, in the future, will be produced using green energy. Consequently, new challenges arise which are specific for each fuel.

The Diesel common rail injector has been developed and refined over several decades [1], [2]. For alternative fuels, however, many questions still need to be answered, or even identified. A reasonable approach is to first develop injection systems on a small scale, in order to detect and address the core challenges of the alternative fuels, and subsequently move to larger engines and production scales with the acquired knowledge. Ganser CRS has therefore designed an injector for hydrogen direct injection for a single-cylinder test engine.

The injector was primarily designed for a single-cylinder test engine with roughly 1L displacement. An injection quantity of approximately 24.5 mg was targeted. The injection duration depends on the injection pressure. The envisioned approach is that the engine operator starts testing with a hydrogen injection pressure of 30 bar. If the targets for power, efficiency and emissions are reached, the injection pressure can then be reduced in increments to investigate if the same values can be reached at lower injection pressures. Accordingly, the injector was designed to deliver the hydrogen mass of 24.5 mg at a pressure of 10 bar, within a reasonable injection duration, as well.

2 INJECTOR DESIGN

2.1 Injector actuation types

Two alternatives were considered for the actuation of the nozzle needle of the injector, both of which present different advantages and disadvantages:

- Direct electric actuation [3]: The solenoid is directly connected to the nozzle needle, pushing or pulling it as needed.
- Electro-hydraulic actuation: Part of the nozzle needle is submerged in hydraulic control oil. Similar to the mechanisms in a Diesel common rail injector, the needle is actuated by generating pressure differences between different areas of the needle. The hydrogen volume is kept separate from the oil volume.

For the direct electric actuation, fewer components are needed. Furthermore, as hydrogen is the only medium in use, no additional sealing is needed to separate it from the control oil.

However, some challenges arise with the direct actuation design. First, the components of the injector are completely dry and not lubricated, which leads to an increased wear of the moving parts. Additionally, the opening and closing of the nozzle needle are not dampened, leading to high impact forces and again high wear on the needle and nozzle. Furthermore, high forces are necessary in both directions. In one direction, high forces are needed to seal the nozzle against hydrogen leakage. In the other direction, high forces are needed to quickly open the needle. These forces need to be either countered or generated by the solenoid, resulting in a large solenoid with high ECU-power demand. This results in a bulky injector design that takes up considerable space in the cylinder head.

With the electro-hydraulic actuation, these disadvantages can be avoided. The control oil serves both as a lubricant and, by the layout of the control hydraulics within the injector, as a damper for the movement of the needle. Moreover, the pressure of the oil can be set several orders of magnitude higher than the hydrogen pressure, making the hydraulic forces the dominant forces in the injector. The pressure differences can be generated in the same way as in a Diesel common rail injector in a relatively small space. Subsequently, the hydraulic forces can at the same time be used to seal against hydrogen leakage and to quickly open the injector and start the hydrogen injection, all while keeping a compact design.

Furthermore, for operation of engines in a power range above 1 MW and with the high compression ratios of a Diesel cycle, often a Micro Pilot Diesel injector (MPI) is used to ignite the main fuel charge [4]. The main charge can be hydrogen, but also one of the other renewable fuels. In that case, Diesel Fuel can be used as well as a drive-fuel for the hydraulic drive of the injection valve for injectors utilized for the main injection charge.

It is evident that, for a fuel differing from hydrogen (H_2), such as methane (CH_4), Methanol (CH_3OH) or Ammonia (NH_3), an injector with the same driving concept and the same outline dimensions can be designed. In some cases, for a given engine type, changing the injector’s nozzle to be suitable for use with a different fuel will be the only major change in the injector. This characteristic allows the engine manufacturer to be more flexible, because the main fuel injector, having the same outline dimensions, will require the same space in the engine’s cylinder head.

Ganser has opted for the electro-hydraulic actuation in this project. The operating principle, design and current test results of the injector are presented below.

The injector measures approximately 250 mm in length and the diameter varies between 11.5 mm at the tip and 60 mm at the top. The necessary connections for the injector operation are depicted in Figure 1.

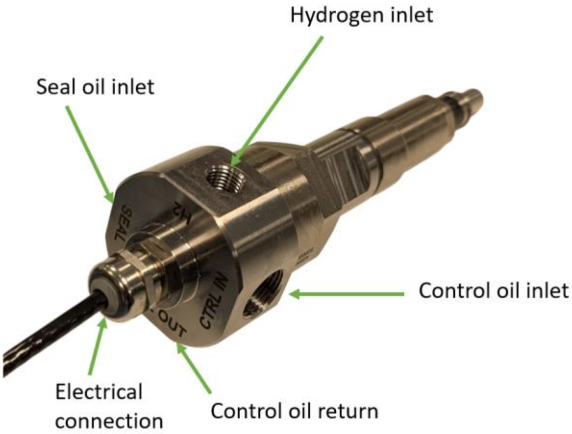

Figure 1. Outline design of the injector

From the inlet at the top, hydrogen flows directly to the tip of the injector, as shown in Figure 2. The passage is designed to be as smooth as possible, with minimal changes in flow direction and cross section, to minimise the pressure losses along the way. A removable cap is mounted on the nozzle, allowing the engine manufacturer to easily test different spray configurations.

The nozzle needle is made up of two pieces, the upper needle (needle 1) and the lower needle (needle 2). This allows for easier and more precise manufacturing and assembly of the injector. A second needle spring (spring 2) is therefore needed as well. It needs to push the lower needle upwards when the upper needle is moving. Its force can be relatively small compared to the upper needle spring (spring 1) which closes the injector when no system pressure is present.

The control oil is pressurized to approximately 300 bar and fed into a chamber containing the top of the upper needle and the hydraulic actuation components, including Ganser CRS' proprietary poppet valve [5], as depicted in Figure 3. The solenoid is mounted above the actuation assembly. The actuation follows the principles used in Ganser's Diesel common rail injectors.

To minimize the leakage from the high-pressure control oil volume into the hydrogen volume, a seal oil passage is used. The seal oil, which is of the same type as the control oil, is directed into a small chamber between the high-pressure control oil volume and the hydrogen volume. In this small chamber, the pressure of the oil is regulated to a level slightly above the hydrogen pressure. Consequently, hydrogen cannot leak to the top of the injector and at the same time, the pressure difference between the oil and the hydrogen, and subsequently the oil leakage into the hydrogen chamber is minimized. Additionally, the needle is mechanically paired with its guiding counterpart, resulting in a small clearance of only a few µm, which further helps reduce the oil flow.

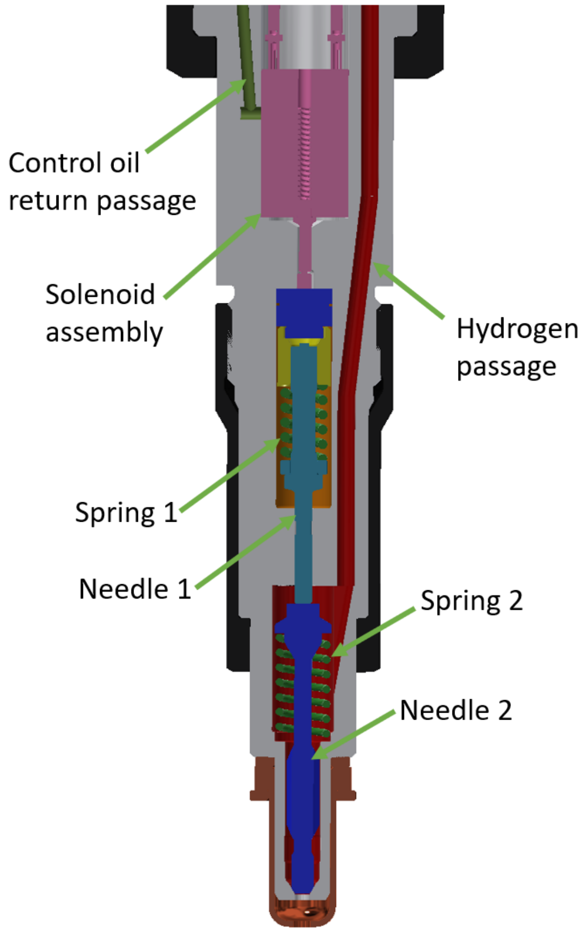

Figure 2. Internals of the injector

The main forces controlling the movement of the nozzle needle are the pressure forces acting on the surfaces S1 and S3, indicated in Figure 3. Surface S3 is a ring surface and its area A_3 is obtained by subtracting A_2 from A_1, which are the areas of surfaces S2 and S1, respectively. Initially, the injector is closed and the complete control oil volume is at the same pressure, p_s, which acts on surfaces S1 and S3. Since surface S1 is larger than S3, the resulting force pushes the needle downward. When the solenoid opens, the pressure above surface S1 drops to p_r, while the pressure acting on S3 remains at p_s. The total acting force on S1, $A_1 \times p_r$, then drops below the opposing force acting on S3, $A_3 \times p_s$, resulting in a net force that pushes the needle upward, initiating the injection. To stop the injection, the current to the solenoid is turned off. The pressure above S1 rises back to p_s, restoring the initial conditions and closing the nozzle needle. The forces of the springs remain approximately constant during the whole opening and closing process and are mainly necessary to hold everything in place when the control oil is not pressurized. The force acting on surface S2 is negligible compared to the hydraulic and spring forces.

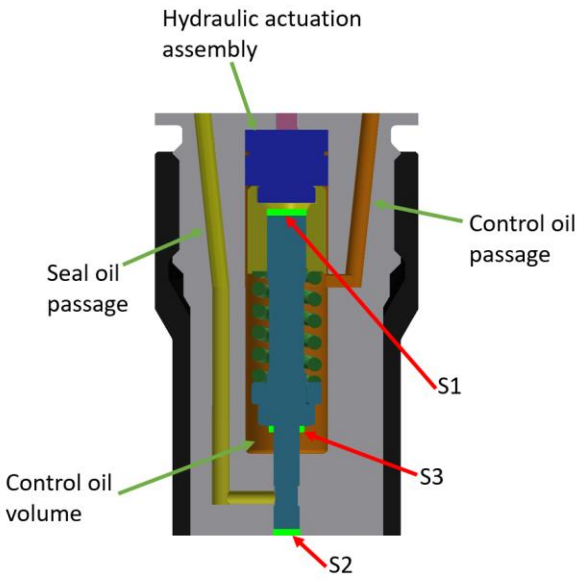

Figure 3. Detailed view of the hydraulic passages and components

3 SIMULATIONS

To check the calculations and the injector concept, a model was set up with use of the 1-D multi-domain simulation software Siemens Simcenter Amesim™. The sketched model of the injector is depicted in Figure 4 with annotations of the components which model the key forces, namely the pressure forces acting on surfaces S1 and S3, as well as the spring forces. One of the major advantages of this software is that all aspects of the injector (pneumatic, hydraulic, electric and mechanical) can be integrated in one model. To optimize the computational costs, some simplifications and idealizations have been made in comparison to reality, such as the response time of the solenoid and some geometries of the pneumatic and hydraulic lines. Furthermore, it would be sensible to inspect and optimize the different domains with more specialized software, which is beyond the scope of this work. For example, the impact of different geometries on the hydrogen flow could be optimized with CFD analyses.

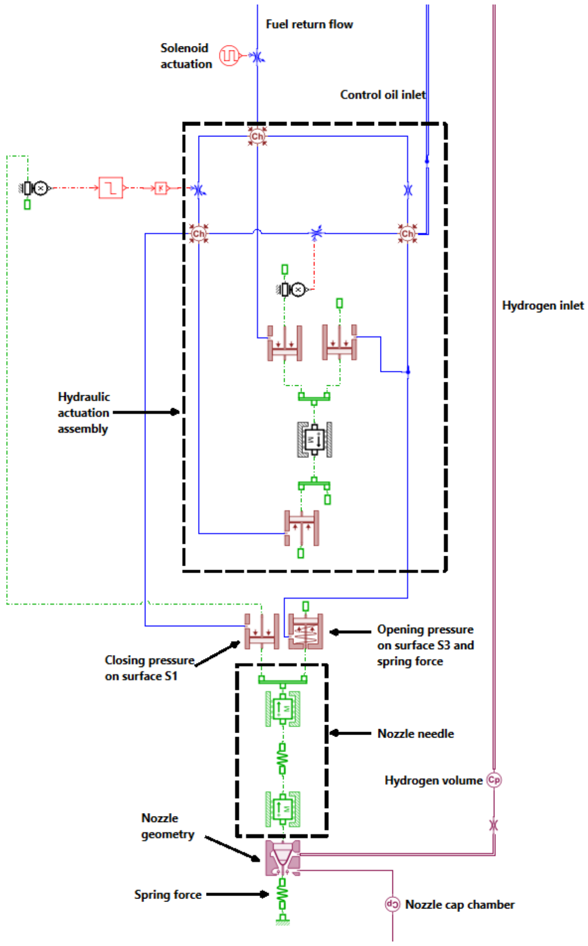

Figure 4. Injector model setup in Siemens Simcenter Amesim™

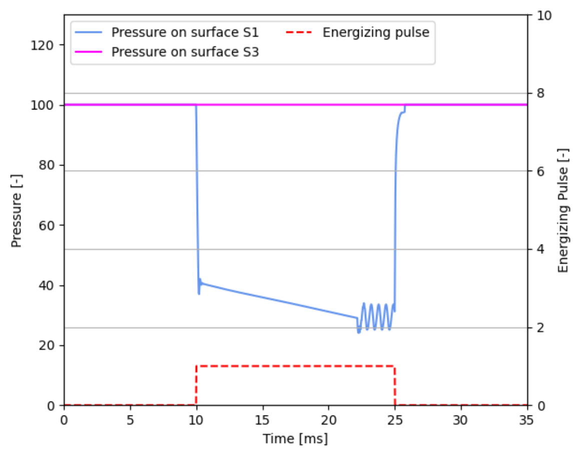

Figure 5. Pressures on surfaces S1 and S3 during an injection

Since the opening of the injector depends on the difference between the pressures acting on different surfaces, the pressures in the various volumes are of interest. In Figure 5, the normalized pressures acting on surfaces S1 and S3 are plotted over time. It becomes clear that the pressure in the control volume above S1 drops drastically, while the pressure on surface S3 remains constant.

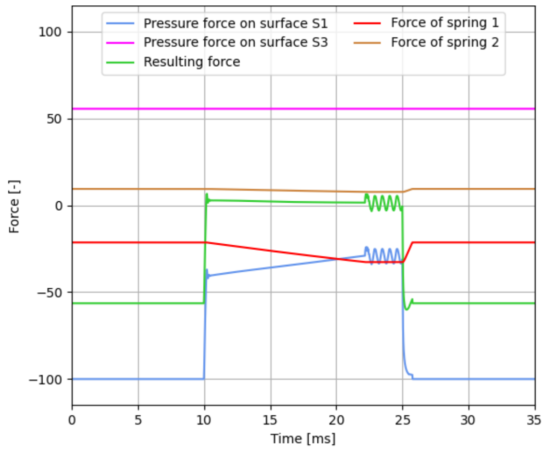

Figure 6. Forces acting on the nozzle needle over one cycle and resulting net force on the needle

The resulting forces exerted by the oil, the spring forces, as well as the resulting net force acting on the nozzle needle were normalized and are plotted in Figure 6. Negative forces push the needle downward, while positive forces push it upward. The plot shows that mainly the force on surface S1 changes, while the other forces remain comparatively constant.

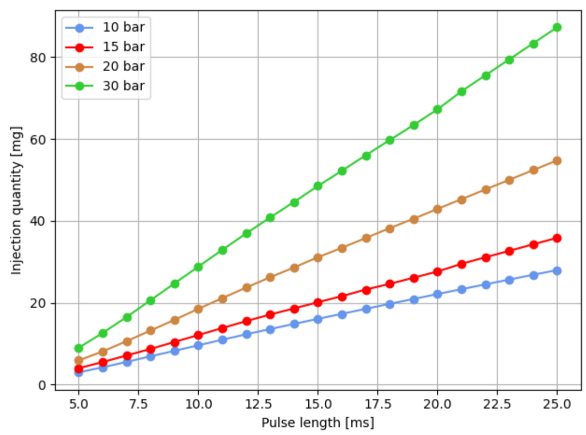

Figure 7. Injector map for hydrogen pressures of 10 bar, 15 bar, 20 bar and 30 bar

The injected hydrogen mass was computed as well and the simulation was repeated for several pressures and pulse durations to generate the injector map shown in Figure 7. The targeted injection mass of 24.5 mg could be met for a pressure range between 10 bar and 30 bar. At 10 bar an injection duration of around 25 ms is necessary to reach the target quantity, which corresponds to 150 °CA at 1000 rpm.

Furthermore, the hydrogen pressure at different points along its passage was analyzed during one injection, as shown in Figure 8. In this way, the features and designs causing the highest pressure losses could be determined and subsequently optimized to minimize the hydrogen pressure losses. This analysis helped identify the hydrogen supply lines from the tank to the injector as having a significant impact on the total pressure drop, as well as on the repressurization of the injector, emphasizing the importance of designing and implementing a suitable supply system for the injection equipment.

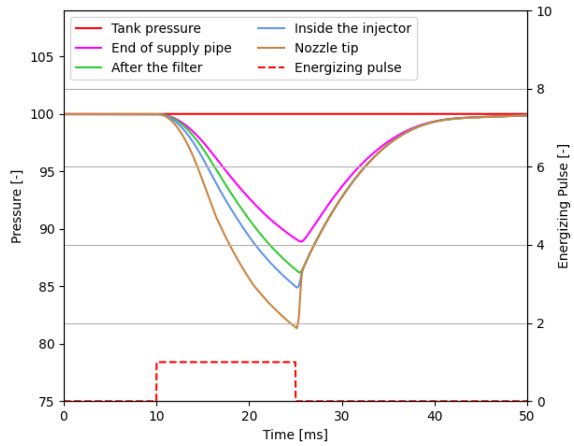

Figure 8. Pressure losses along the way from the hydrogen tank to the injector tip

4 TESTS

Before testing with hydrogen, leakage and functionality tests were conducted with nitrogen and helium. These gases offer a good alternative for basic tests, as they are cheaper and safer than hydrogen.

Following successful completion of the initial tests, further tests were carried out with hydrogen to evaluate the injectors' performance under conditions more representative of engine operation. Two injectors were tested during this phase, and the results are presented in the following subsections.

4.1 Leakage test

Since hydrogen is highly diffusive and requires careful handling, leakage tests have been performed before engine operation.

No leakage was detected on the first injector at any hydrogen pressure. However, small leakage was detected at the tip of the second injector. This leakage has been measured at different hydrogen, control oil and seal oil pressures. The results are presented in Table 1. No leakage was detected at any other location on the injector.

Table 1. Measured hydrogen leakage at the tip of injector No. 2

Hydrogen pressure [bar]	Control oil pressure [bar]	Seal oil pressure [bar]	Hydrogen leakage [Nml/min]
10	15	15	0
10	300	15	0
20	25	25	21.4
20	300	25	3.2
30	35	35	49.2
30	300	35	7.9

One of the advantages of the hydraulically actuated injector becomes apparent when looking at these test results: the force exerted by the control oil on the needle substantially reduces the hydrogen leakage or even prevents it completely.

4.2 Injection tests

The injector maps were recorded for different hydrogen pressures. With these, the engine operator has the certainty, that the injector delivers enough fuel for the engine to operate. Furthermore, they serve as verification of the simulations. The maps obtained from the simulations and tests can be compared and the simulation model and parameters can be tuned to better reflect reality.

The simulated injection quantities were well aligned with the test results, with an average deviation of around 1.1% from the results of injector No. 1 at 20 bar. However, the discrepancies were more noticeable at 10 bar, with an average deviation of approximately 33.4%. Hence, the simulations were reviewed and parameters such as flow coefficients were adjusted to better match the test results of injector No. 1 at all pressures. The comparison between the tests and updated simulations are shown in Figure 9. While the largest discrepancies remain at 10 bar, the average deviation was reduced to around 14% from the test results. The results at the remaining pressures, especially at 15 bar and 30 bar, show an excellent match with the test results.

The differences between both injectors may stem from minor differences in geometries coming from the manufacturing process. For example, small differences in the seat diameter of the nozzle needle can have an effect on the flow cross sections, which influence the flow behaviour of the gas. Hence, precise manufacturing, especially of the smallest flow cross sections, are essential for consistent and repeatable injections across several injectors.

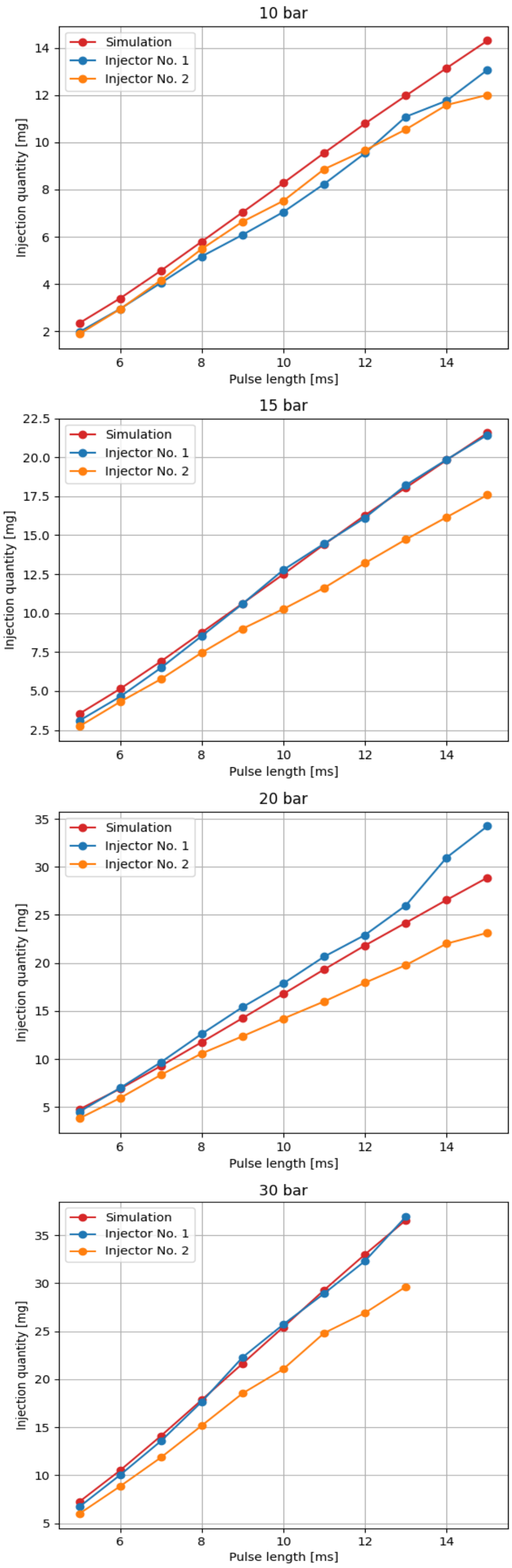

Figure 9. Injectors map at 10, 15, 20 and 30 bar hydrogen pressure: comparison between simulation results and measurements for two injectors

Figure 10 shows the hydrogen jet recorded in a spray visualization chamber. The spray has a good penetration depth. Different spray configurations can be tested by using nozzle caps with different hole patterns.

Figure 10. Visualized hydrogen spray

5 CONCLUSIONS AND OUTLOOK

The design, simulation, and testing of an electro-hydraulically actuated hydrogen injector for direct injection were described in this paper. The working principle is based on the well-established Diesel common rail injector concept. While the focus of this work was on hydrogen, the injector can be adapted for several alternative fuels with minimal modifications.

The use of high-pressure control oil generates forces of several hundred newtons on small surfaces. This allows for quick injector dynamics while keeping the design compact with a comparatively small solenoid. Furthermore, the hydraulic oil and high forces help sealing against hydrogen leakage.

The simulation results accurately predicted the injector's behaviour in many scenarios. The injection tests confirmed these results and demonstrated that the target injection quantities could be reached for all pressures in the range of 10 to 30 bar. However, some discrepancies between the simulations and the tests still remain, highlighting some of the limitations of the current simulation methods.

Finally, it is worth emphasizing that the injector concept presented in this paper is scalable and can be adapted for larger applications, such as large-bore engines. In such cases, higher forces are required to open and close the nozzle needle and seal against hydrogen leakage. Thanks to the electro-hydraulic actuation, this can be achieved by increasing the control oil pressure or slightly enlarging the surface areas, allowing the injector to retain the original solenoid and a compact size.

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