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Application & experience of a pilot controlled DI Gas-& Hydrogen injector– on marine engine

Fuel Injection & Gas Admission and Engine Components

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ABSTRACT

This paper illustrates experiences in development and application of a modular, pilot-controlled Gas- & Hydrogen-injector concept, the design definition, the technical performance field, the CFD simulations, set up the hardware for measurement in function and results on the injector test bench and on a single cylinder test engine, in order to cover the large variance of fuel applications and combustion processes. DUAP and ITAZ have developed specific DI injectors in a modular design, to support the CO2 free conversion of powertrain system with internal combustion engines in heavy-duty truck-, industrial- and marine applications. The test results show very high reproducibility between shot to shot, even in ballistic operation mode and demonstrates, that volume spreads up to 1:60 between idling and full load are possible. Due to the system-related flexibility in the injector control valve (at identical magnetic force for all strokes), needle strokes of up to 750?m have been realized for passenger cars/trucks and up to 1mm for large bore medium speed engines.

Due to the modular injector concepts, we present furthermore also the achieved injection rates in smaller high-speed applications, e.g. 48g/s at 80bar and 34g/s at 50bar and engine speed up to 9000 rpm. The very short injection times supports the combustion process due to longer time of mixing the fuel gas with the intake air. That leads to a better, homogenous mixture. The current H2 injection quantities range are from 1 to 100 mg per injection for car/truck applications and from 5 to 1800 mg per injection for large bore, medium speed engines in marine power systems. Fuel pressures between 5 to 80 bar and up to 500 bar can be achieved for (special) high-pressure applications. Due to the high needle dynamics in the force-compensated pressure design, multiple and post-injections are possible at combustion chamber pressures of up to 85% of the system pressure. Due to the ingenious mechanical system, no lubrication is required and the tightness achieved at the nozzle is

1 INTRODUCTION

The primary driver of global warming is the gradual worldwide increase in the carbon oxide (CO_2) concentration in the atmosphere. To cover the world's steadily increasing energy demand still fossil fuel reserves are used, which are known to be exhaustible and which mainly lead to this increase in the CO_2 concentration in the atmosphere [1]. The largest source of CO_2 emissions is the burning of fossil fuels (coal, oil, natural gas) for energy production, transportation, and industrial activities.

For the maritime industry, the International Maritime Organization (IMO) has set strict emission reduction targets, such as the IMO 2020 regulation capping sulfur emissions and the IMO's greenhouse gas (GHG) strategy aiming to reach net-zero GHG emissions (compl. decarbonization) by or around 2050. [2].

Marine combustion engines, especially those powered by heavy fuel oil, are significant contributors to greenhouse gas emissions, particularly CO_2. As the global shipping industry accounts for approx. 3% of worldwide CO_2 emissions, improving internal combustion engine (ICE) efficiency and reducing emissions must be done within the next 25 years to meet international climate goals.

Driven by the negative impacts of the global warming and the international valid regulations, to reduce the greenhouse gas emissions, the Maritime industry is exploring and shifting towards alternative, cleaner fuels (such as liquid natural gas (LNG), biofuels, methanol, hydrogen, and ammonia). Alternative fuels and innovative engine technologies are solutions, to achieve these decarbonization goals.

Large bore ICE's have a lifetime of 20 - 30 years at least. Therefore, the fastest and most economical way to reduce GHG emissions is, to adapt existing marine combustion engines with technologies, they can operate these new fuels. This ensures that the industry can be convert to sustainable energy sources, within the given time.

This paper presents the application and operational experience of a pilot-controlled direct injection (DI) gas- and hydrogen injector on a four-stroke marine medium-speed engine. Key performance metrics and operational challenges were analyzed to evaluate the feasibility of hydrogen and other burnable gas as alternative fuels in marine propulsion systems.

2 INJECTION & IGNITION CATEGORIES FOR GAS- AND HYDROGEN-ENGINES

In a first step we evaluated the most efficient and environmentally friendly injection principle for gaseous energy carriers, out of following technologies:

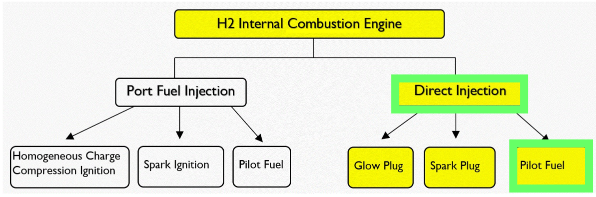

Figure 1. Categorization of Gas- / Hydrogen Internal Combustion Engine (ICE) based on typical injection and ignition strategies [3].

The result of this evaluation led to the decision to develop a modular injector concept for the direct injection (DI) of gaseous fuels into the combustion chambers of IC-engines.

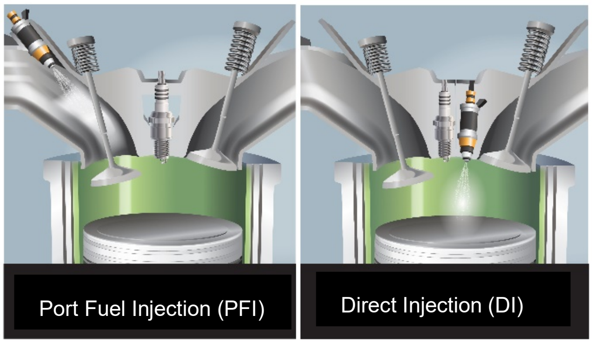

Figure 2. Comparison of PFI- and DI-Injection. Picture © 2024 The Lubrizol Corporation

The next chapter summarizes the advantages of the direct injection concept of gaseous fuels.

2.1 Gas/Hydrogen direct injection principle

Despite the higher complexity and costs of DI injection systems in combustion engines, the advantages of DI concepts outweigh the disadvantages.

For this reason, the DI concept was implemented for the development of this Gas-/H2-Direct injector family, blows in gaseous fuels (incl. Hydrogen) directly into the combustion chamber. The DI concept enables the supply of a higher volume of gas/hydrogen, which provides sufficient energy for combustion and a diesel-like power output.

Table 1. Advantages of Gas/Hydrogen DI-injection

Advantages of Gas DI- versus PF-injection
Improved fuel efficiency due to precise control over the timing and quantity of injected fuel
Higher power/torque output due to more effective combustion. Especially for marine engines, which need to deliver consistent power.
Better Emissions Performance DI allows stratified charge combustion (lean burn), which reduces CO_2, NO_x, & PM emissions compared to PFI. IMO Tier III. It helps meet stringent marine emissions regulations such as IMO Tier III standards.
Flexibility in Fuel Management GDI systems can handle variable combustion strategies, including homogeneous or stratified charge modes, improving versatility for varying operational demands.
No Gas/Fuel slip into the intake manifold. This protects the environment and avoid uncontrolled combustion into the intake manifold. No backfire.
Reduced Knocking DI enables better control over fuel delivery and combustion, reducing the risk of knocking. This allows the engine to operate at higher compression ratios, increasing overall thermal efficiency.
Enhanced Cold Start Performance DI engines perform better during cold starts, making them advantageous in marine environments where engines may operate in colder climate conditions.

In a further step, all physical and commercial framework conditions and marked demands, influencing our DI injector concept, were analyzed and summarized in a specification sheet. Facts are:

Marine medium-speed engines typically operate in power range, from 150–2’000 kW/cyl @250-1’000 rpm, are used in commercial marine applications and prioritize efficiency, performance, operational flexibility, reliability and compliance with emissions standards.

Natural Gas and specifically Hydrogen as fuel has a much lower energy density by volume compared to liquid fuels like HFO, MDO or Diesel fuel, especially at ambient pressure.

Hydrogen is the most abundant element in the universe and offers a promising, clean alternative solution to traditional marine fuels, with the potential to reduce emissions and improve air quality. Once hydrogen production and the necessary infrastructure are available, hydrogen will become a more widely available fuel source, reducing dependence on finite fossil fuels such as oil and natural gas. As soon technologies for sufficiently, economically hydrogen production are available, it will become a more widely available fuel source, reducing dependency on finite fossil fuels like oil and natural gas. [4]

As hydrogen has a higher flame speed and a wider ignition limit than conventional fuels, special ignition systems are required. In addition, the engine control system must be precisely tuned to ensure stable and controlled combustion and power.

2.2 Modular injector concept

The development of modular and flexible injectors that can be used to operate both high-speed motors and large size medium-speed engines was another task. The following requirements profile was the basis for the development of these injectors.

Table 2. Injector development requirements

Flexible for different engine sizes with a high volume spread of e.g. 15 - 1,700 mg full load quantity for hydrogen
Flexible for different, direct injecting fuel gases or gas mixtures (blends)
Small-quantity capability for stable idling and low load operation
High dynamics for the shortest injection times with high injection volumes
Fuel pressure flexibility in terms of rail pressure from 5 bar up to 500 bar
Gas jet guiding for better homogeneity
Dry-running capability and low control leakage
Minimal wear behavior, e.g. due to reduced seat forces at the injection valve
Easy to control
Robust for different applications as heavy duty and Marine
Sustainability in the use of technology and materials

The first design was used for classic applications in the car- and truck-engine sector. For this purpose, positive tests have already been carried out on various single-cylinder engines up to 90kW.

In order to operate the same injector concept in large size medium speed engines, these results were used as a basis.

2.3 Injector working principle

The pilot-operated injector design significantly enhances the flexibility of injector parameters. This means needle stroke and nozzle diameters can be selected very freely within the scope of the application. The resulting amount of control gas (the same as the fuel gas) can easily be fed into the intake manifold or even used for exhaust gas aftertreatment, if available. Our experience shows the feasibility of recirculating to the air intake area, upstream of the turbocharger or into the intake manifold. The following image explains the principle.

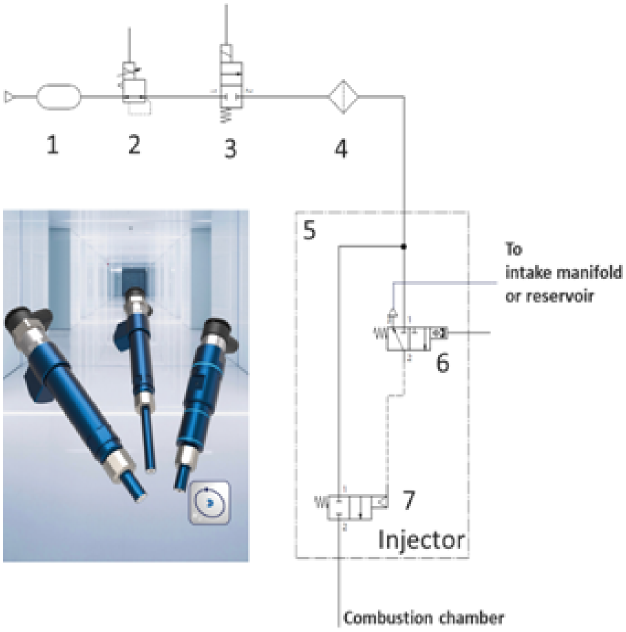

Figure 3. Working principle of the pilot controlled DI-injector, Picture © 2022, ITAZ GmbH, Germany

Legend:
1. Gas tank
2. Pressure control valve
3. Shut off valve
4. Filter
5. DI-injector
6. Pilot control valve
7. Injector needle valve

2.4 Injector function

Number 5 represents the injector, which includes a pilot valve number 6 to control the injector needle. By opening the valve number 6 the needle starts moving, the injection process begins. By closing the valve number 6, the needle closes, the control gas used to open the needle, which is around 1% or less of the total injection amount, will be guided into the intake manifold before the turbo charger or to a similar position.

2.5 Injector sizes and injection volumes

Figure 10 explains the current DI-injector family. The development started with 2 injectors for passenger and truck vehicles 0,5 liter and 2,2 liter cylinder volume. The injector with the 18mm nozzle diameter can be used for a 4 liter cylinder volume. At the bottom, the injector with 33mm nozzle is used for 500kW per cylinder. This type of injector will be described in more details in this paper.

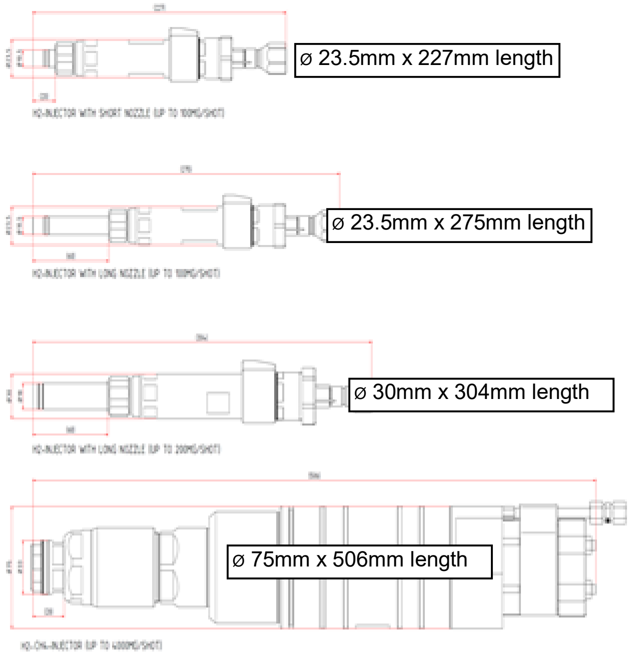

Figure 4. Current modular DI injector family from ITAZ and DUAP

With the 500 kW DI-injector type, the injection volume of Methane spreads between 0.5g/cycle up to 5g/cycle, at 50bar gas pressure and 25°C temperature.

The control leakage of this DI injector family is max. 1% of the injected gas volume over all load points.

The injector is driven by the fuel gas. No separate actuating medium is required.

The development-, simulation- and engine test results of the small injector were presented at the CIMAC congress 2023 in Busan, paper #128 [6].

This paper shall present now the current development and test status of the large size DI-injector for 500kW/cyl in medium speed engines.

2.6 Large size medium speed engines

The pilot-operated DI-injector principle can be scaled very flexible in timing, flow rate and speed. In order to achieve a cylinder output of 500kW, per cylinder, @720rpm, on a 4stroke medium speed engine, the following injector design with an injection quantity of 1750mg H2 for full load was developed, manufactured and tested.

Figure 5. Large size DI-Injector. © 2023, DUAP

3 MEDIUM- AND HIGH PRESSURE GAS-/ HYDROGEN DIRECT INJECTORS

The direct injection of gaseous fuels, and in particular hydrogen, presents a large range of challenges and parameters that need to be solved in order to meet the requirements of a well-functioning internal combustion engine.

For example, short injection times are very important in order to have sufficient time for homogenization. A high flexibility of the gas jet guide to support the development of the combustion process, but also an increased robustness of the injector to meet the service life requirements of dry lubrication.

The focus of this injector concept is the free controllable supply of gaseous fuels to the combustion chamber of IC-engines with a cylinder power up to 500 kW @750rpm.

DI Gas-/Hydrogen injectors for this high power range are currently rare in market. Today we can offer 2 versions of these DI-injectors:

- MPDI-DI-Injectors up to 80bar

- HPDI-DI-Injectors up to 600bar

3.1 Fuel supply system requirements

The fuel supply chain from the tank to the injectors, the injection strategy, and fuel injection equipment (FIE) play a critical role in combustion quality and overall engine performance. Clear defined comprehensive specification documents was developed, provided and negotiated with the provider of the gas supply system.

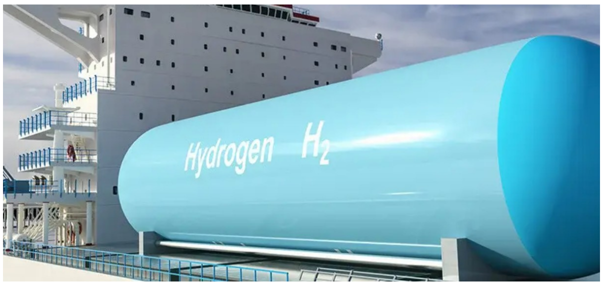

Figure 6. Hydrogen high pressure storage solution. Symbol picture © 2024, Habonim, USA

For high-pressure hydrogen storage and supply systems in particular, it is advisable to work with suitable companies.

4 DEVELPOMENT, SIMULATION, TESTS

Parallel to the development, design work and prototype hardware tests, all functions of this DI injectors were calculated and analyzed by 1D-Simulations.

Due to the fact that the volume to be injected with gaseous fuels is up to 8 times higher than with conventional diesel fuel, the main requirement was to make the injector timing as fast as possible. Combustion development with internal mixture formation requires DI injectors with steep opening and closing profiles.

4.1 Simulation of Gas-/H2 DI injection

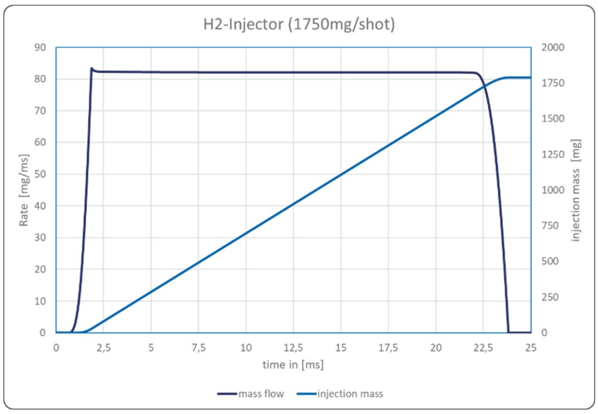

Figure 7. H2 Simulation of injection rate and injection quantity at 30 bar gas pressure

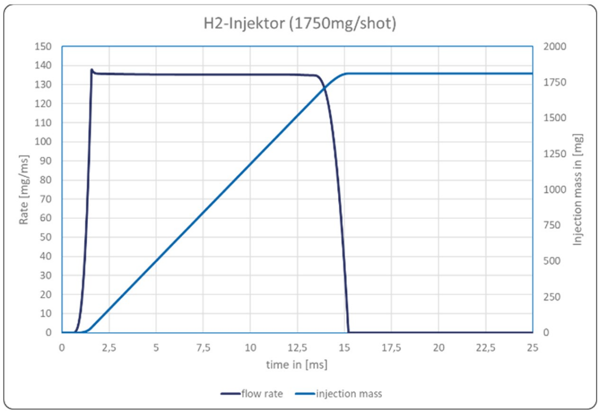

Figure 8. H2 Simulation of injection rate and injection quantity at 50 bar gas pressure

A small but absolute stable gas amount for idling is also an important parameter. Besides the large gas quantity for full load, it must also be possible to inject the idle and low load quantity in a stable manner.

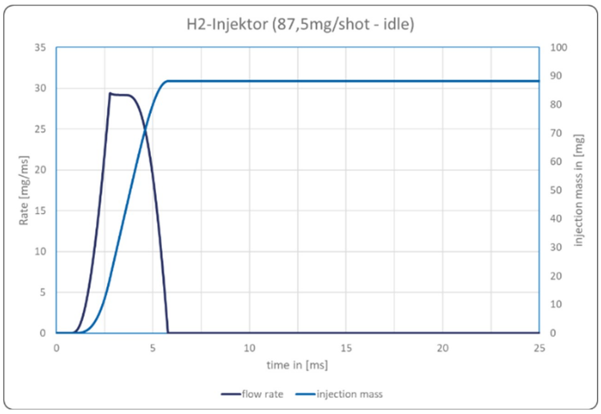

Figure 9. H2 Simulation of smallest injection rate and quantity

Adjusting a small ballistic stroke of the needle is also feasible with this design. The ability to hold the needle in the exact position for a longer period of time allows for very easy control of the smallest amount. With a simple peak and hold actuation of the actuator, all the smallest quantities can be adjusted with sufficient time. The supply spread between the smallest and the highest gas quantity can be with this injector between 1:50.

The ballistic function can be adjusted over a certain pressure range and thus the injection quantity can be finely controlled. An example is the measurement in the following image.

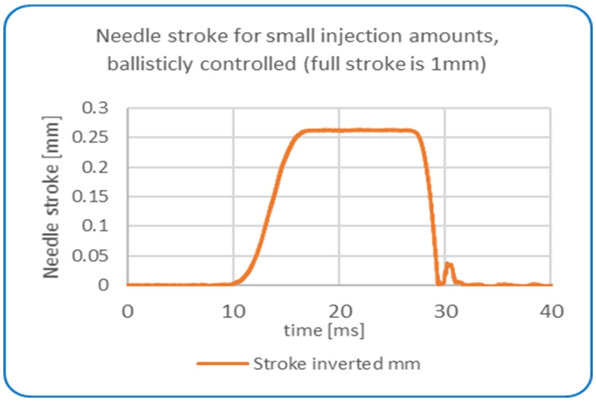

Figure 10. Measurement of needle stroke under ballistic conditions, test medium Helium

Functional measurements confirm comparable results of the 500kW full-load injector compared to the small 50kW injector. The opening time of the needle is approx. between 2-20ms and allows the gas to be injected quickly into the combustion chamber. The advantage resides in the homogenization of the gas with the air, the fast availability of the gas provides more time to achieve the better lambda values.

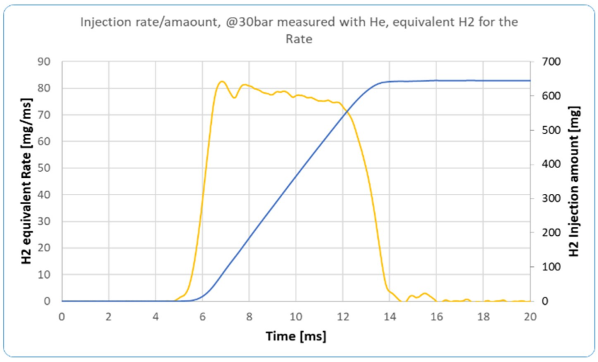

Figure 11. Injection rate and quantity with Helium

5 MEASUREMENT INTO THE PRESSURE CHAMBER

5.1 Injector test into the pressure chamber

Before using this DI injector in the test engine, it was tested and measured in the pressure chamber of the LKV Institute at the University of Rostock, In the pressure chamber we were able to measure all relevant gas injection parameters and the safety elements.

The measured data of the injector performance from the pressure chamber were compared with the simulation data and the values from the injector test bench. The test medium into the pressure chamber was Nitrogen to simulate methane (CH_4).

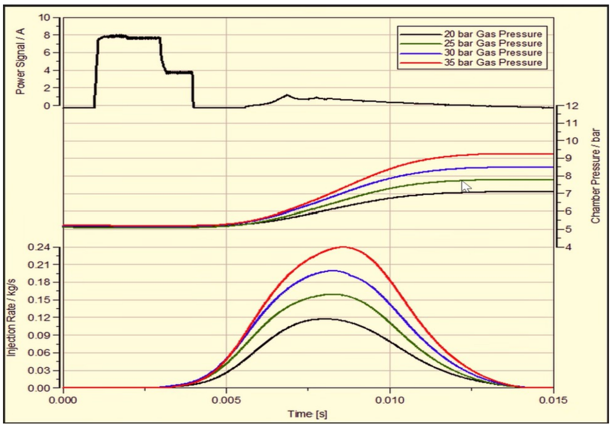

Figure 12 Nitrogen Injection rate and timing at different pressures. Source: LKV, Rostock

Figure 12 shows the solenoid actuation signal, the injection rate and the chamber pressure at different gas pressure levels and ambient temperatures. Test medium Nitrogen.

These tests are important to ensure that the injector functions properly over the entire load range of the engine. From engine start to low idle speed and from low load to the overload range.

5.2 Measurements with Methane (CH4)

The identical measurements in the same pressure chamber but with CH4, led to the same results as measured with nitrogen. So we continue with CH4.

At an injection amount of around 1000mg/shot, the variability of 45 shots is within a range 2,6%.

Figure 18 shows the overlaying of 45 shots for the injection rate and injection quantity. The precise repetitions can be seen.

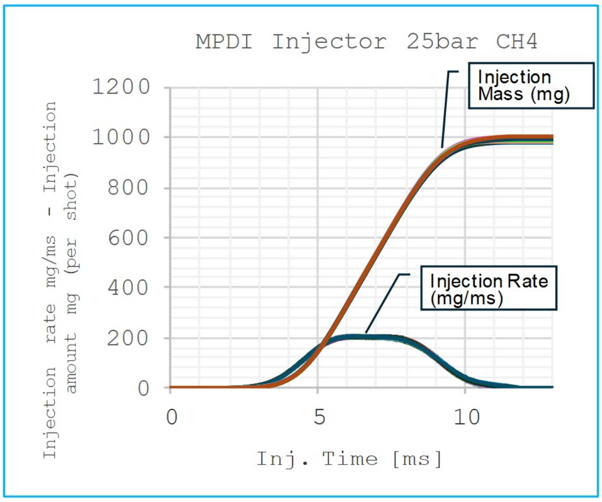

Figure 13. Measurements of injection rate and quantity with CH4 at 25 bar & 45 injection cycles

5.3 Heating values of gaseous fuels

The following table is for information purposes. One part of this injector concept also includes the operation of this injector type with other gaseous fuels and their mixtures, until sufficient worldwide availability of CO2-free gas fuels. All these gases can be used with this injector concept.

Table 3, Heating values of some gaseous fuels, source: combustion engineering, 2nd edition, Borman, Ragland

Gaseous fuel	MHV (medium heating value) in **MJ/m3**	MHV (medium heating value) in **MJ/kg**
Hydrogen (H2)	10.8	131.7
Carbon monoxide (CO)	11.6	10.1
Methane (CH4)	34.6	52.8
Ethane (C2H6)	61.6	49.9
Propane (C3H8)	87.2	48.4
Butane (C4H10)	112.5	47.7
Ethylene (C2H2)	55.9	48.8
Acetylene (C2H2)	52.3	49.1
Propylene (C3H6)	81.5	47.4
Natural gas	36.5	50.9
Coal producer gas	4.8	4.9
Wood produce gas	4.4	4.7

5.4 Injector durability test on a test rig

Parallel to the tests in the pressure chamber, we carried out durability tests with this injector on a test bench. The test medium was Hydrogen and the injector was heated to 90°C. The first test simulated an equivalent of approx. 100 engine running hours.

The aim was to test the injector with Hydrogen, at 50bar and under unlubricated conditions, similar to how the injector must function in a real engine.

Meanwhile we collect in total more than 1'000h test hours, until now without negative results or excessive wear on the components. The endurance tests will be continued.

We are aware that 1,000 hours does not yet meet the requirements of the market. However, with the current injector concept, we can offer a robust and reliable DI-injector solution for the development of combustion processes with gaseous fuels.

6 SINGLE CYLINDER ENGINE TESTS

6.1 SC test engine

The LKV laboratory of the University of Rostock operates one of the largest 4stroke single cylinder combustion research engine in Europe.

Figure 14. Test engine Caterpillar MaK M34DF-SCE / 4stroke, Source: LKV laboratory of the University of Rostock

Table 4. Specification of the SC test engine

Caterpillar MaK M34DF-SCE / 4stroke	
Cylinder bore diameter	340 mm
Piston stroke	460 mm
Displacement	41.76 Liter
Compression ratio	12.75
Rated speed	720 rpm
Rated power	> 500 kW
Peak firing pressure	> 200 bar
Pilot fuel system for (Bio-) Diesel	DUAP MPI-CR-System, decentral pos.
Max. Pilot fuel pressure	1'500 bar
Gas-/ Hydrogen DI-injector	DUAP & ITAZ, central pos. in cylinder
Gas injection pressure	5 – 600 bar abs
Max. charge air pressure	8.5 bar abs
Dynamometer	1.2 MW
ECU	National Instruments PXI
EGR	up to 30 % @ 100 % load

6.2 Engine setup

The engine setup is based on a single-cylinder engine with 500 kW rated power for use with the gas DI injector. The current setting is 50 - 80 bar gas pressure, with the option of using different types of gas.

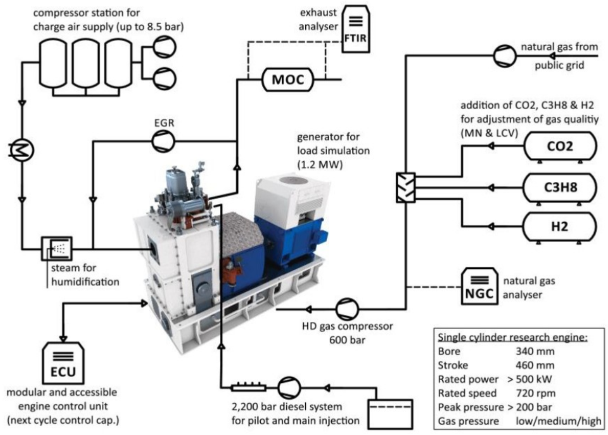

Figure 15. Single cylinder test engine, Source: LKV laboratory of the University of Rostock

6.3 Gas- & MPI-Injector configuration

For the DI-injector test of the SC –engine we used our own DUARAIL Micro Pilot Ignition System as illustrated in the following figure. We have more than 20 years of positive experience with MPI-Ignition Systems on large size medium speed gas engines.

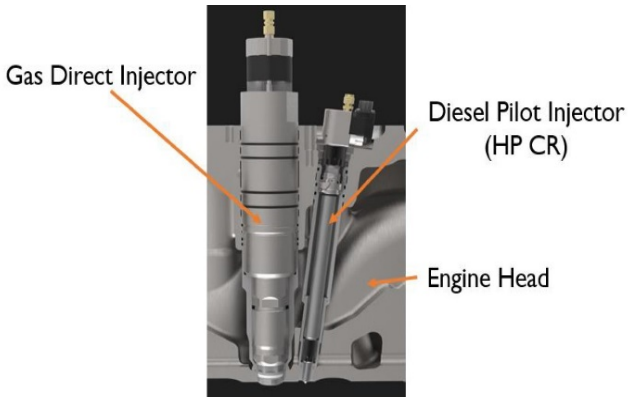

Figure 16. Injection- and Ignition-concept on the SCE test engine [5]. Gas/Hydrogen DI injector & MPI injector in cylinder head

Out of the different fuel injection and ignition possibilities, mentioned in Fig.1, the test setup on the single cylinder test engine in the LKV-Laboratory of the University in Rostock was finally according this basic evaluation, PFI & MPI.

A concept with two different injectors, one for Gas/Hydrogen DI-Injection and the other for the Micro Pilot Ignition System.

The configuration with 2 separate injectors offers more flexibility in the retrofitting or re-engineering of existing combustion engines. E.g. conversions from a HFO- to a gas-engine.

6.4 Injector position into cylinder head

Optimal combustion and energy conversion rely on the precise formation of a homogeneous air-gas mixture. Achieving this requires careful calculation and coordination of key factors as the position of the injectors, the intake/outlet valve placement into the cylinder, the air charge system, airflow dynamics, nozzle design, and the injection jet pattern.

A central located gas injector into the cylinder head, paired with a Micro-Pilot-Ignition system positioned near the center, appears to be the preferred solution

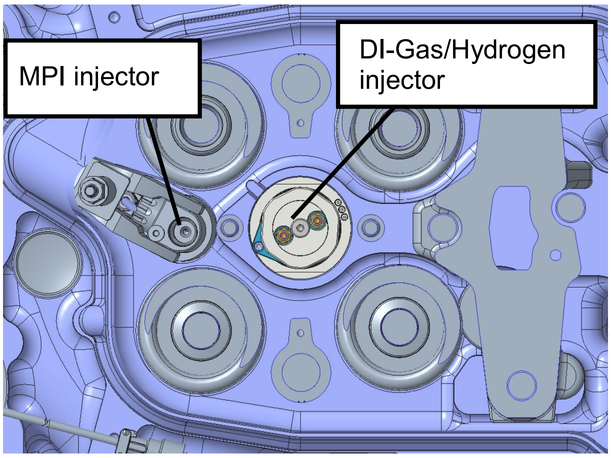

Figure 17. Injector positions of the DI- and the MPI-Injector. View from top.

6.5 Engine load management

The SC test engine operates along the generator curve up to 720 rpm at various load conditions, representing a standard application for medium-speed marine engines. It is managed by a fully programmable research-grade engine control unit (ECU), which enables real-time pressure monitoring and next-cycle adjustments. Measurements are conducted at a frequency of 1 Hz, with certain parameters, such as in-cylinder pressure, being recorded at intervals of 0.1° crank angle (CA) and synchronized with the rotation of the crankshaft.

6.6 Engine injection simulation

The injection simulation done by LKV Rostock shows the potential of the DI injection. Using the right timing, the air fuel mixture is homogenous enough to get into a good combustion. This leads to higher efficiencies since also the fuel mass can be higher than with PFI injection.

A further advantage is, the concentration of fuel gas, near to the wall (cylinder liner) is nearly zero, due to the central position of the injector and the conically guided gas jet. This protects the lube oil film along the cylinder liner. The backflow of gas into the manifold is practically not measurable, even the injection occurs during the inlet valve opening time.

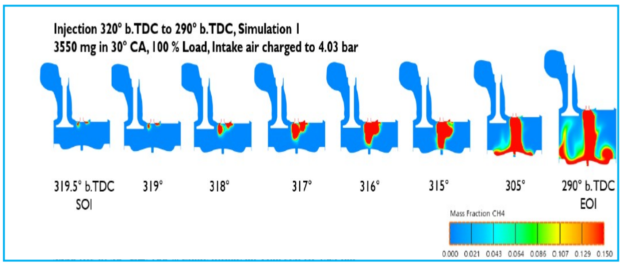

Figure 18: Injection of Methane into cylinder [5]

6.7 Homogenization of air and fuel

At 180° CA the gas and the air are already well mixed due to the turbulence of the intake air flow. There are lean areas under the intake valve furthest from the intake manifold and under the exhaust valve furthest from the exhaust manifold. Although the mixture is well homogenized by 10° CA before TDC, these areas remain slightly leaner. The flow patterns are similar to those found in the low pressure port fuel injection operation, although not identical. The degree of homogenization can be seen in figure 19.

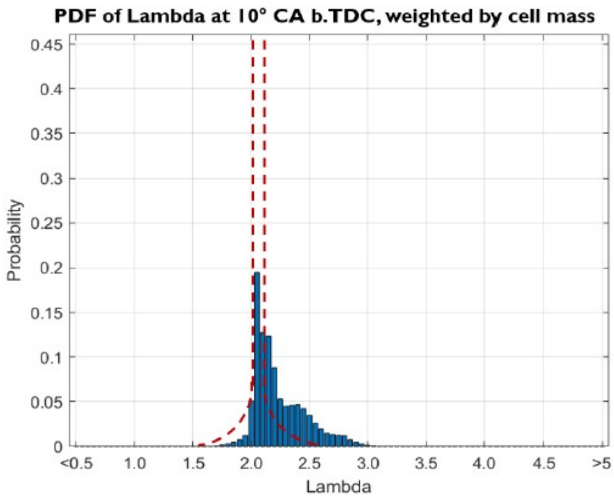

Figure 19: Lambda distribution with DI injection

6.8 Safety aspects

Safety is a critical consideration in the design and the operation of Gas-/ Hydrogen-fueled marine engines, as the use of gases like CNG, LNG, Hydrogen or Gas blends presents unique risks such as fuel leaks, explosion hazards, and fire risks. To eliminate these risks, several safety measures are implemented across various stages, from fuel tank and delivery to engine operation and emergency response.

Gas-fueled marine engines must comply with international safety standards, including those set by organizations such as the International Maritime Organization (IMO), or authorized Classification Societies.

7 ENGINE TEST RESULTS

As a next step, engine tests have been performed to get data and gain experience with the injector and engine.

In a first step, the test engineers on the engine adjusted the DI-injector to operate the same cylinder pressure curve, timing, power and torque as with the current SOGAV port fuel injection system. The MPI-Ignition system remains the same for the PFI- and the DI-engine tests. Fuel gas was CH4.

The aim of this test was to find out whether it is possible to operate the DI gas injector, respective the gas engine, even at low fuel gas pressures of 4-6 bar and without a methane slip.

Following graph shows that is was possible to operate the DI injector, respective the gas engine with the same performance as in PFI configuration. In DI mode, the methane slip was below the measurement limit.

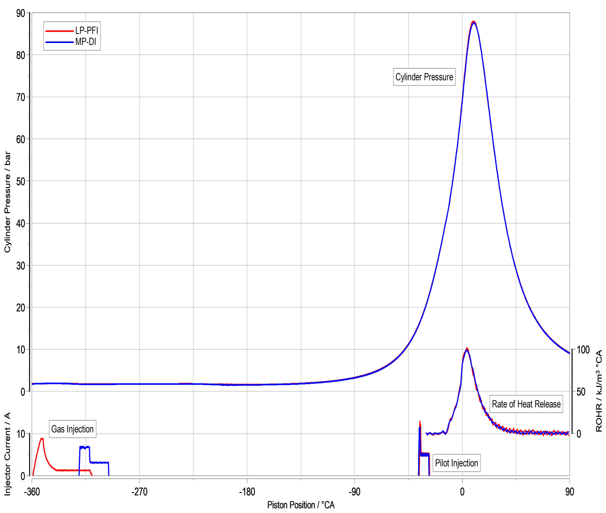

Figure 20. Comparisson for low pressure PFI- and low pressure DI-injection, at 50% engine load with CH4. LKV, University of Rostock

One specific test was to understand the impact of the injection timing and the corresponding engine result. 10 different timing positions have been selected to investigate the engine variability. The ignition is done with a diesel pilot injector at the same timing. The result is a very robust engine performance. Independent from the time of gas injection, the cylinder pressure is very stable and repeatable.

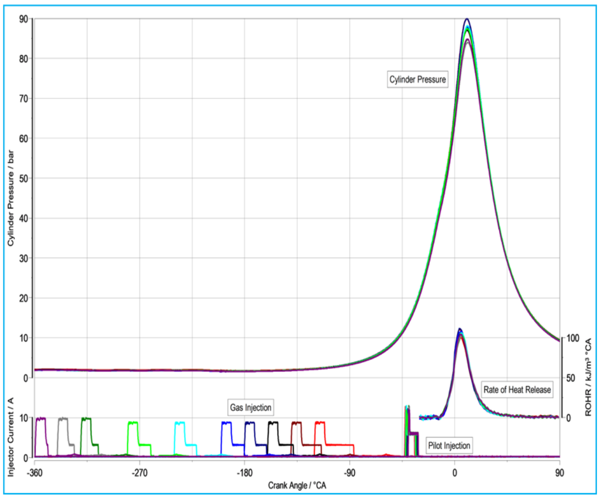

Figure 21. Engine measurements with natural gas. LKV, University of Rostock

The NOx emission are getting higher as closer the gas injection is positioned to TDC. More detailed results are currently collected.

8 MATERIALS

Hydrogen diffusion and the resulting hydrogen embrittlement pose significant challenges for metallic materials, especially in sectors such as energy generation, aerospace, and as well for fuel injection components. Hydrogen can penetrate metals, accumulate at interstitial sites or defects, and lead to embrittlement. During the prototyping phase we had to developed preventive methods to mitigate these effects.

8.1 Hydrogen diffusion

Hydrogen diffuses through metals via grain boundaries, dislocations, and other defects. The diffusion rate depends on the metal structure, temperature, and hydrogen concentration. Face-centered cubic (FCC) structures exhibit lower diffusion rates compared to body-centered cubic (BCC) structures.

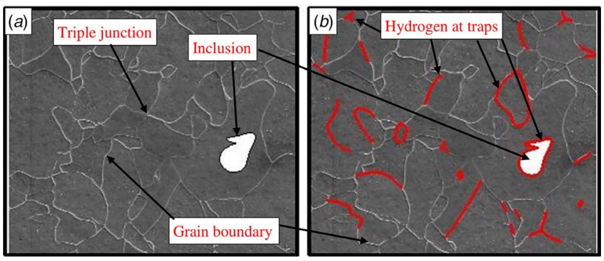

Figure 22. Symbolic illustration of Hydrogen diffusion / Unit cross-sectional area of a X70 steel sample: (a) before polarization and (b) after

polarization. Source: Materials Science and Engineering, Volume 865, 16 February 2023, © by the Authors.

8.2 Hydrogen embrittlement

This occurs through interactions between hydrogen atoms and the metal's microstructure, leading to phenomena like hydrogen-induced cracking (HIC), stress corrosion cracking (SCC), and hydrogen-induced loss of plasticity. Mechanisms include hydrogen accumulation at defects and weakening of metal-metal bonds.

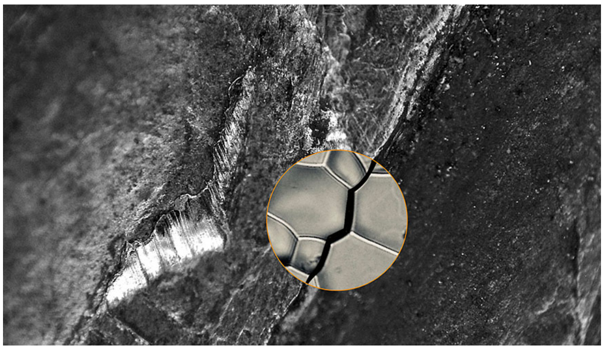

Fig 23. Symbolic illustration of Microscopic crack in nickel alloy caused by hydrogen embrittlement. © Dharmesh Patel, Texas A&M University, College of Engineering, Livermore, USA

8.3 Methods to prevent Hydrogen Diffusion

Diffusion Barriers: Coatings such as oxides, ceramics, or polar polymers effectively inhibit hydrogen diffusion (e.g., aluminum coatings forming Al_2O_3 or TiN layers).

Alloy Development: Adding elements like chromium, nickel, or vanadium reduces diffusion by forming intermetallic phases that hinder hydrogen movement.

Surface Modification: Techniques like gas nitriding layers, laser treatment or ion-based surface processes alter surface structures to reduce hydrogen uptake.

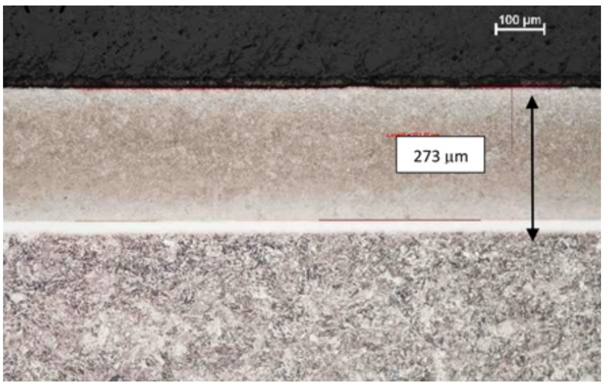

Figure 24. Alloy 431 cross-section after gas nitriding. Source: Journal of Minerals and Materials, 2023, © Beth Shemesh Engines Ltd.,Israel

8.4 Methods to prevent H2 Embrittlement

Stress Reduction: Methods like annealing or stress-relief heat treatments minimize residual stresses in metals.

Microstructure Optimization: Fine-grained structures reduce hydrogen accumulation at grain boundaries, achievable through thermo-mechanical treatments.

Hydrogen Traps: Alloys can be designed to include hydrogen traps (e.g., carbides, nitrides, or fine dispersive precipitates) that bind hydrogen in harmless states.

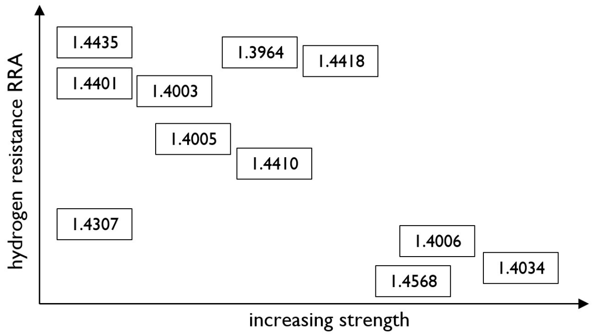

Figure 25. Hydrogen resistance stainless steels [6]

In summary, the engine tests show that damages caused by hydrogen to the injector components can be prevented if the above-mentioned material properties, heat treatments and surface coatings are taken into account.

The fatigue strength of other engine parts against hydrogen was not the subject of this test series

9 SUMMARY & CONCLUSIONS

To summarize the current development stage and the collected test results, we can say that concentrating on the DI injection principle in combination with a suitable ignition system was the right decision, to provide the customers a modular and flexible injector for gaseous fuels including pure Hydrogen.

The engine results confirm the measurements on the functional test bench and the CFD simulations. The stability and performance of this DI injector concept are clearly visible. The values of the parameters checked during measurements can be detected with a good correlation.

We know for sure, that the development of this DI injector family is not finished yet. Essential is to collect more data about, the combustion process, the energy conversion, the emissions, the efficiency and the consumption.

Measurements on emissions and environmental influences are currently being carried out on the test engine. What already can be confirmed is that with the DI-injector the Methane slip is reduced to a non-measurable value.

Therefore, we will continue the development and testing work to gain more experience with real engine applications, injector performance, injector efficiency, injector manufacturing and service experience in the market.

The next project steps are, to execute the already ongoing combustion development projects with leading medium speed engine manufacturers and integrate the DI injection technology into their engine concepts.

The engine tests with the 500bar high pressure DI injectors are scheduled in summer 2025, on the same SE engine in the University of Rostock, as we used for the medium pressure tests mentioned above. Information about these tests follows.

As a conclusion we can say, this injector concept offers many advantages for injecting gaseous fuels into the combustion chamber.

This DI injector concept can be used for new engine designs as well as for conversion projects for already existing engines to support the efforts in reduction of emissions from marine sector.

10 DEFINITIONS, ACRONYMS, ABBREVIATIONS

10.1 Nomenclature

CA	crank angle
CFD	computational fluid dynamics
CH4	Methane
CNG	compressed natural gas
CO2	carbon dioxide
c-chamber	combustion chamber
DOI	duration of injection
DI	direct injection
EGR	exhaust gas recirculation
FIE	fuel injection equipment
g	gram
GHG	green house gas
H2	hydrogen
He	Helium
ICE	internal combustion engine
kW	kilo Watt
MFBx	mass fraction burned %
MPI	Micro pilot injection
ms	milli seconds
NG	natural gas
NGDI	natural gas direct injection
Nm	newton meter (torque)
NOx	nitrogen oxides
p	pressure
PFI	port fuel injection
RNG	renewable natural gas
SCR	selective catalytic reduction
SOI	start of injection
ROI	rate of injection
rpm	rotation per minute
R^2	regression
RRA	relative reduction of area
s	second
SOI	start of injection
TDC	top dead center
µm	micro meter

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