Hydrogen Direct Injection for Medium-speed Combustion Engines

Hydrogen direct injection in medium-speed large engines is considered a particularly promising solution for the realization of almost CO_2-free operation of combustion engines. ITAZ and DUAP are developing a new pilot-controlled and modular hydrogen injector family for different engine sizes.

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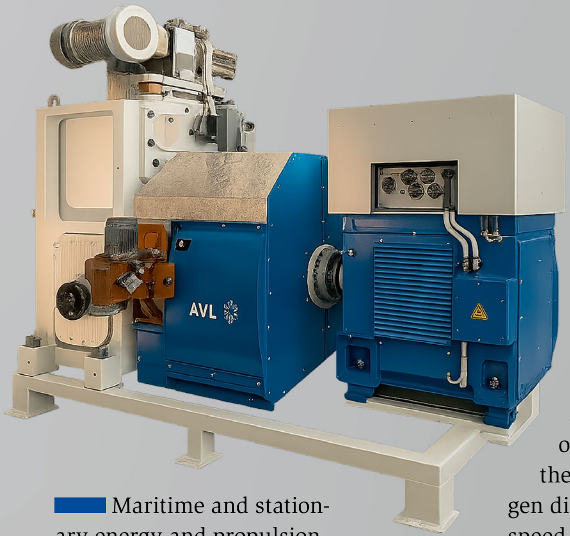


FIGURE 1 Single-cylinder engine test bench (© DUAP)

Maritime and stationary energy and propulsion technology is in a phase of far-reaching structural change. Driven by global climate targets, stricter regulatory requirements and increasing social pressure to decarbonize, the basic technological conditions of large combustion engines are changing fundamentally. Fossil fuels still dominate the global energy supply today and thus make a significant contribution to increasing the CO_2 concentration in the atmosphere. The international shipping sector accounts for around 3 % of global CO_2 emissions and, with the MEPC-83 targets of the International Maritime Organization (IMO), is faced with the task of drastically reducing its emissions and eliminating net zero greenhouse gases (GHG) by 2050.

Since large ship engines and stationary large units with outputs of over 2000 kW per cylinder are often in use for 30 years or more, a complete change in technology is neither economically nor logistically feasible in the short term. Converting existing platforms to carbon-free/neutral fuels such as hydrogen, ammonia gas, e-methane, gas-capable injection concepts therefore offer a viable way to reduce emissions quickly and massively without having to completely replace the underlying infrastructure. Hydrogen direct injection (H_2-DI) in medium-speed large engines is considered a particularly promising solution for the realization of almost CO_2-free operation of combustion engines.

MOTIVATION FOR HYDROGEN AND DIRECT INJECTION

Initial applications of hydrogen-powered gas engines work predominantly with homogeneous premixing via the intake manifold. However, these premix processes are associated with self-ignition tendency, backfire risks and limited load capabilities, as the hydrogen in the intake manifold displaces the air and thus has less total gas available, especially at high load points. The direct injection eliminates hydrogen in the intake system and thus prevents a backfire into the intake module. It enables optimal filling, as the air is already in the combustion chamber, enables high power densities and significantly improves efficiency as well as the controllable combustion characteristics.

Fired engine tests in the laboratory of the University of Rostock, **FIGURE 1**, also show that the centrally located medium-pressure direct injection system enables particularly uniform mixture formation and gas accumulation at the cylinder

FIGURE 2 Potential applications for gas injectors (© DUAP)

FIGURE 3 CFD injection simulation (upper left) and lambda distribution (© ITAZ)

walls can be avoided, thereby protecting the lubricating oil film and reducing emissions. By means of a targeted jet guide, the gas can also be injected in a targeted manner and distributed very evenly in the combustion chamber.

REQUIREMENTS FOR INJECTOR TECHNOLOGY

The injection of gaseous hydrogen places high demands on injectors and their actuators. The nozzles in medium-speed engines (300 to 1000 rpm) must ensure extremely short opening and closing times, high mass flows, operational reliability with dry lubrication, sufficient resistance to hydrogen embrittlement and a high level of thermal robustness. The dry-running capability implemented by appropriate surface systems, is important in order to avoid lubrication oil entering into the engine, due to injector lubrication, which would generate additional CO_2.

The pilot-controlled injector family presented meets these requirements through a modular concept for different engine sizes, precisely controllable needle strokes, injection quantities from a few milligrams to over 1750 mg of hydrogen per cycle. A flexibly usable operating pressure range between 5 and 80 bar, very low control losses of less than 1 % of the injected quantity, as well as high robustness and long service life. In the applications, an operating pressure of 20 to 40 bar is usually used. This provides a scalable system that can be used in high-speed engines (up to 10.000 rpm for example in sports cars) as well as in heavy, medium-speed marine propulsion systems and power plant engines, **FIGURE 2**.

INJECTION STRATEGIES AND COMBUSTION PROCESSES

The operating pressure of the injector concept can be flexibly adjusted from 5 to 80 bar. Typical applications are used for pressures in the range of 20 to 30 bar, which offer the chance to empty the tank system to a low level. Typical injection times for full load are 20 to 24 ms.

In order to penetrate into the combustion chamber against higher cylinder pressure levels, injection can also be used at 30 to 80 bar. This is achieved by means of flexible fuel dosing to inject the injection quantity into the combustion chamber in a very short time or to perform another late injection in the area of already elevated compression pressures.

The late injection just before TDC produces a mixture that is not completely homogeneous, but locally ignitable, can be used in the transient range to help the dynamics and performance of the engine, in order to support high load requirements.

Graduated multiple injections can have a positive effect on NO_x formation. Gas mixing can also be supported. After-injection can also be used for exhaust gas aftertreatment to reduce NO_x in the catalytic converter more effectively.

SIMULATION RESULTS AND FLUID MECHANICS

CFD simulations show the central injection of hydrogen into the combustion chamber, **FIGURE 3**. The concentrated jet shape allows the injection to be started with the inlet valve still open and helps homogenization by taking more time. Deep penetration is made possible by a targeted jet guidance, which injects the hydrogen at speeds of over 2000 m/s. Therefore, the upward movement of the piston starts and supports the mixing process of the hydrogen with the air at an early stage. Lambda values between 2 and 2.5 are achievable. An optional stratified charge with a corresponding piston recess further centers the hydrogen gas. Fuel build-up near the cylinder wall is avoided and this reduces leakage into the crankcase.

The lambda values are determined shortly before the mixture is ignited. Since NO_x formation depends strongly on the lambda, this value is essential. Any lean or rich regions that may be present can be specifically taken into account in the engine application.

TEST BENCH AND ENGINE RESULTS

The injector can be operated continuously at 5 to 30 bar from the smallest injection masses to full load. Even at higher pressures, good linearity is present in order to be able to operate the injector for almost all quantities, **FIGURE 4** (left). This capability makes it easy to use on the engine. To achieve stability on the engine, attention was paid to the good repeatability of the injections during the development of the injector. The shot to shot measurements based on needle stroke variability (equivalent to injection mass) show an impressive coverage accuracy. The deviations within the population are less than 2 % at 30 bar. This can also be achieved at lower and higher pressures, **FIGURE 4** (right).

Engine tests with methane and hydrogen have yielded reproducible results compared to diesel applications. Thus, gas applications can replace existing applications well. Studies with different ignition angle positions show a very stable combustion over a large area despite large time differences with hydrogen. Hydrogen seems to burn wel in all positions.

On the engine, four load points were successfully driven with methane. The firing process was stable and repeatable in all respects, **FIGURE 5**. Conversely, this also means high injection stability for the injector, as well as good shot-to-shot results. Respectively, the emissions are correspondingly good and controllable.

EMISSIONS AND ENVIRONMENTAL ASPECTS

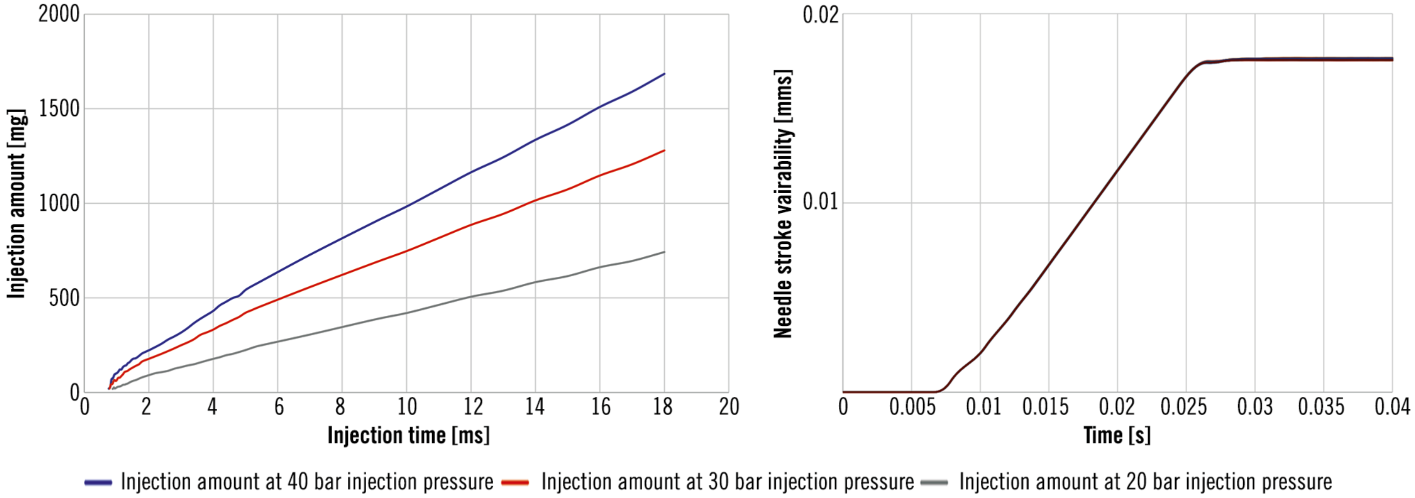
The combustion of hydrogen in large ship engines is particularly advantageous in terms of CO_2, NO_x and particulate emissions. Since hydrogen contains no carbon, there are virtually no CO_2 emissions from the fuel, apart from minimal proportions from lubricating oil combustion. Particle emissions are almost completely eliminated, as no soot or particulate matter formation can take place without carbon. NO_x formation, on the other hand, remains challenging, especially with lambda 1. With lambda around 2.3, the engine can be operated almost without exhaust gas aftertreatment. Good homogenization is the prerequisite for stable NO_x control. This significantly reduces exhaust gas aftertreatment and reduces costs.

INTEGRATION AND SYSTEM ASPECTS

The use of hydrogen as a CO_2-free energy carrier in maritime propulsion technology and stationary energy generation places high demands on integration and system design. These include the quality of hydrogen, hydrogen transport and refueling logistics, safety guidelines and coordination with hybrid energy systems. In marine and large engine applications, the focus is particularly on the integration of suitable hydrogen storage systems – either in the form of cryogenic tanks or as 350 up to 700 bar high-pressure systems – as well as the safety architecture. Hydrogen direct injection engines are particularly suitable for ferries, offshore suppliers, coastal and inland waterway vessels.

Stationary systems can also be pipelined directly to the engine.
In stationary energy plants, standalone grids or emergency power generators, the main focus is on flexibility, load change behavior and grid support. Hydrogen direct injection engines offer high efficiencies, enable fast load changes and largely use existing gas or diesel platforms, which makes conversion much easier. Integration into local or regional hydrogen infrastructures – such as electrolysis, storage and transport chains –is in-

FIGURE 4 Injection characteristics at different pressures (left) and needle stroke shot to shot at 20 injections (right) (© ITAZ)



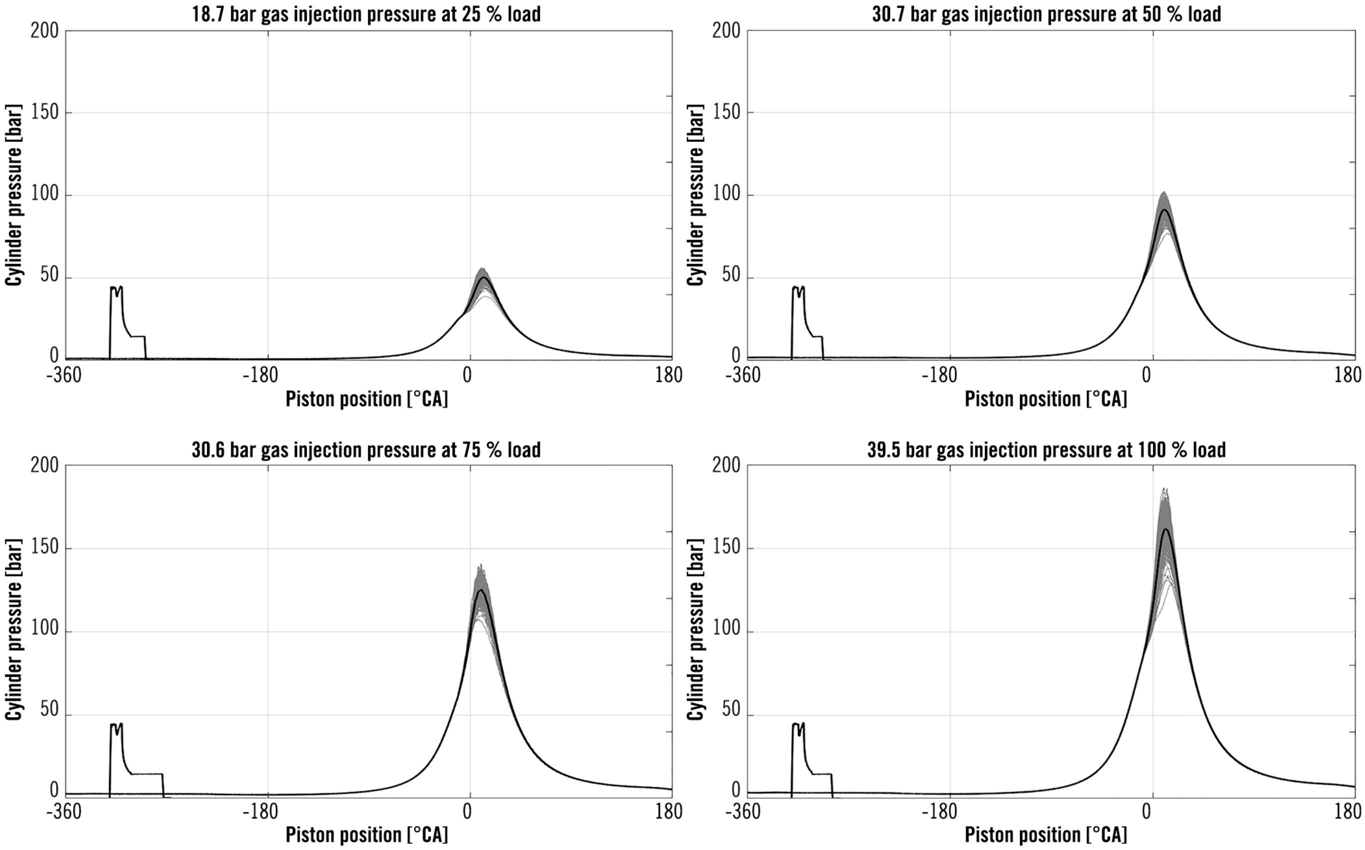


FIGURE 5 Engine pressure curves with methane at different load points (© University of Rostock)

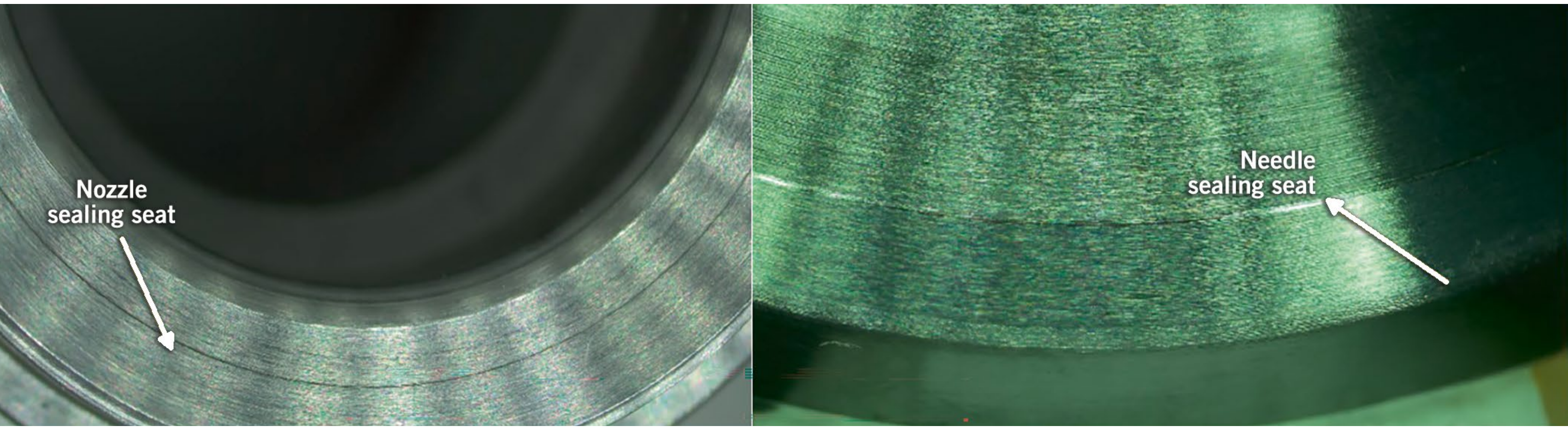


FIGURE 6 Nozzle and needle seat after about six million cycles comparable to around 280 engine hours (© ITAZ)

creasingly becoming a decisive factor for economic viability.

Hydrogen direct injection engines are significantly cheaper to procure than fuel cells of comparable performance and require less high-purity hydrogen. Thanks to its high robustness and long service life, it has a good life cycle assessment, especially with renewable hydrogen supply, **FIGURE 6**.

OUTLOOK

It is expected, that first commercially usable hydrogen direct injection engines for maritime propulsion systems and stationary combined heat and power plants to come onto the market within the next five to ten years, especially as standards and regulatory frameworks for applications and emissions become increasingly established. At the same time, the technology will continue to develop more robust injection systems, higher injection gas pressures up to 400 bar, optimized ignition and combustion strategies and material solutions. This reduces technical risks and profitability pays off. In the long term, hydrogen direct injection will be a stable technology – especially for applications where fuel cells or batteries are impractical, for example at high power, continuous load, or heavy infrastructure demands.