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System architectures for HPDF injection of PTX-fuels on large marine engines

Fuel Injection & Gas Admission and Engine Components

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ABSTRACT

The marine industry is forced to adopt various means to reduce the environmental impact of shipping emissions and must continue to innovate and invest in sustainable solutions to achieve a low-carbon future. Alternative fuels like ammonia and methanol are playing a significant role in this transition.

For both fuels, there are two possible combustion processes: pre-mixed combustion and diesel-like combustion. Pre-mixed combustion involves mixing the fuel with air before it enters the engine cylinder and then igniting the mixture with a spark or a pilot diesel injection, which will be the choice for some dual-fuel engines as used in marine applications. This process is similar to the combustion process used in established dual fuel four-stroke gas-engines. Diesel-like combustion involves injecting the PTX fuel directly into the engine cylinder at high pressure and igniting it immediately with a diesel pilot. This process is similar to the combustion process used in diesel engines and can provide similar efficiency and power output as the same engine in diesel-mode.

The expected fuel cost for green methanol and green ammonia is likely to be higher than traditional fossil fuels due to the increased costs associated with producing these alternative fuels.

Efficient combustion processes are therefore crucial when burning these fuels in internal combustion engines to minimize fuel consumption and harmful emissions simultaneously. To achieve the lowest-possible carbon emission output with a dual-fuel engine, a high substitution rate (replacing fossil fuel with P2X fuels like ammonia or methanol) is also of high importance.

The logical choice to achieve these goals is therefore a diesel-like combustion, which requires a high-pressure direct injection of methanol or ammonia and a pilot diesel injection.

Disadvantage of such a combustion process is the complex fuel injection system involving a diesel injector and a methanol or ammonia high-pressure injector and the corresponding high-pressure pump and piping.

However, with an optimal system architecture, complexity and cost of such systems can be reduced.

Several years ago, Woodward started to develop a high-pressure dual-fuel injector family that incorporates a diesel injector and a methanol or ammonia injector in one unit. This technology has continuously matured and is now being applied in several development projects with leading engine OEMs.

To further reduce system complexity, Woodward will introduce a high-pressure pump for methanol and ammonia that is designed as an on-engine component.

The paper will give a summary on the HPDF injector family concept design and touches on challenges faced during the development. It will also introduce a pump concept for P2X fuels and give an outlook on next development steps.

1 INTRODUCTION AND MOTIVATION

The shipping industry forms the backbone of global trade, enabling the movement of approximately 90% of the world's trade by volume. While indispensable for economic activity, this sector comes with substantial environmental costs. Shipping emissions significantly contribute to atmospheric pollution, negatively impacting air quality, marine ecosystems, and human health.

Globally, shipping is responsible for approximately 2.5% of greenhouse gas (GHG) emissions, primarily in the form of carbon dioxide (CO_2). Despite continuous efficiency improvements, emissions from the shipping sector are projected to remain stable or decline only slightly by 2050 due to increased global trade, far away from meeting decarbonization targets [1]. These emissions worsen global warming and contribute to climate change, leading to rising sea levels, extreme weather events, and widespread disruptions to marine and terrestrial ecosystems. In addition to GHGs, the shipping industry emits sulfur oxides (SO_x), nitrogen oxides (NO_x), and particulate matter (PM), which further harm the environment and human health.

1.1 Drivers for Decarbonization

The International Maritime Organization (IMO) has been instrumental in developing global regulations to reduce emissions from shipping. In 2023, the IMO updated its initial GHG strategy (set in 2018). The earlier target of reducing GHG emissions by at least 50% by 2050 has been revised to aim for full decarbonization of the shipping sector by around 2050 [2]. Intermediate targets include reducing annual GHG emissions by at least 20% by 2030 and 70% by 2040, compared to 2008.

Beyond the IMO's global framework, regional bodies have implemented stricter measures to address GHG emissions. The European Union (EU) is at the forefront of these efforts.

Under the European Commission's "Fit for 55 legislative package", the FuelEU Maritime Regulation (Regulation (EU) 2023/1805) promotes the use of renewable and low-carbon fuels, as well as clean energy technologies for ships. The regulation sets maximum limits for the yearly average GHG intensity of energy used by ships above 5,000 gross tonnage calling at EU ports.

Additionally, the EU Emissions Trading System (ETS) includes maritime emissions starting in January 2024. The ETS applies to CO_2 emissions from ships above 5,000 gross tonnage entering EU ports. It covers 100% of emissions for voyages between EU ports and 50% for voyages where either the departure or arrival port is outside the EU. From 2026 onward, methane (CH_4) and nitrous oxide (N_2O) emissions will also be included [3].

But the drive for marine decarbonization is not limited to regulatory efforts. Leading corporations are increasingly adopting ambitious sustainability goals, with a particular focus on reducing Scope 3 emissions - those generated throughout their value chains, including transportation and logistics. Companies like Amazon, Nike and IKEA have set aggressive decarbonization targets in alignment with the Paris Agreement and growing consumer demand for environmentally responsible practices. Amazon for example, through its Climate Pledge, is committed to achieving net-zero carbon emissions across its operations by 2040 [4]. This includes addressing emissions from global shipping, a critical component of its supply chain. IKEA aspires, amongst other targets, to reduce the relative GHG emissions from product transport by 70% by 2030 compared to baseline 2017 [5].

These corporate commitments are driving demand for low-carbon logistics, placing significant pressure on the shipping industry to adopt greener technologies and fuels.

1.2 Trends in Marine Decarbonization

To meet regulatory requirements and corporate demands, the shipping industry is increasingly adopting sustainable practices. Key trends include:

1. **Energy Efficiency**:
   Energy-efficient technologies and practices are being implemented across the industry to reduce fuel consumption and GHG emissions. These include improved hull designs, air lubrication systems, and operational changes like slow steaming.

2. **Digitalization**
   Advances in digital technologies are enabling optimized route planning, predictive maintenance, and real-time fuel consumption monitoring. These innovations help shipping companies to reach lower emissions while improving operational efficiency.

3. **Alternative Fuels**
   The industry is exploring alternative fuels to achieve significant GHG reductions. These activities include liquefied natural gas (LNG), biofuels, green methanol, and green ammonia. These fuels offer varying degrees of carbon reduction potential, with green ammonia and methanol emerging as promising candidates for net-zero emissions.

While energy efficiency improvements and digitalization strategies are crucial for reducing greenhouse gas (GHG) emissions, they alone are insufficient to fully decarbonize the marine sector. A fundamental shift away from fossil fuels is imperative to achieve net-zero emissions.

In this context, alternative, sustainable fuels such as green methanol and green ammonia have emerged as promising candidates. These so-called Power-to-X fuels (PTX-fuels) are synthesized using renewable energy sources to power electrolysis. The so-produced hydrogen is then combined with nitrogen (for ammonia) or carbon dioxide (for methanol) through catalytic reactions.

Research into combustion concepts of these fuels for maritime applications began around 2015 and quickly progressed to fuel-system and engine development programs. Initial efforts focused on two-stroke main engines, followed by advancements in four-stroke engines, which typically feature highly integrated injection systems.

The transition to these sustainable PTX-fuels fuels offers several options to operate combustion engines. However, the choice of fuel is less constrained by engine technology—despite challenges inherent to emerging systems—and more influenced by the availability of PTX-fuels and the feasibility of on-board storage solutions tailored to the specific operational demands of each vessel.

2 PTX-FUELS FOR MARINE ENGINES

2.1 Methanol and Ammonia as fuel

The physical properties of methanol and ammonia differ significantly from fossil-based marine fuels such as Heavy Fuel Oil (HFO) or Marine Diesel (MDO), as summarized in Table 1, necessitating new concepts in storage, fuel preparation, injection, and combustion.

As a consequence, the conversion of a vessel to use either methanol or ammonia has a significant impact on the fuel- and engine system. The following sections examine key aspects of this conversion and the corresponding solutions from the perspective of a fuel injection system supplier.

Table 1: Fuel properties

	Diesel (EN590)	Methanol	Ammonia
Liquid energy density [kWh/m^3]	980	480	320
Phase State	liquid (T< 150°C)	liquid (T< 65°C)	liquid (T < - 33°C or p > 9bar)
Vapor pressure (@ 20°C) [bar]	0,01 - 0,1	0,13	8,6
Toxicity	uncritical	toxic	toxic & strong odor nuisance
Corrosion behavior	uncritical	challenging	challenging
HFRR/MFPRR (tribology) [µm]	< 460	approx. 800 (dep. on H2O cont.)	No test setup
Viscosity [mm^2/s]	2-4	0,7	0,15
Compression-Modulus [N/mm^2]	1300	1000	1700
Vaporization Enthalpy [kJ/kg]	250	1160	1368
Self-ignition temperature [°C]	250	455	630

3 COMBUSTION STRATEGY

Different combustion methods for methanol and ammonia as fuels are widely discussed in the literature, each requiring distinct injection systems that are already being implemented on various engine types [6].

The primary distinction between combustion strategies lies in their fundamental combustion principles: on one hand, there is homogeneous premixed combustion following the Otto cycle, and on the other hand, there is heterogeneous combustion following the Diesel cycle.

Currently, marine engines utilizing sustainable fuels are predominantly dual-fuel engines, designed to operate with a fallback option for full diesel-fuel operation. This approach is largely driven by classification society regulations mandating redundancy for safety and reliability, but also by the current uncertainty surrounding the global fuel supply infrastructure. However, as requirements for fuel systems are defined, it is equally important to consider the demands of monofuel engines to prepare for future advancements in fuel technology.

3.1 Homogeneous Otto-combustion

The Otto combustion principle is widely known from gasoline-powered on-highway applications. In this process, fuel is injected either into the intake manifold (Port Fuel Injection, PFI) or directly into the cylinder (Direct Injection, DI) during the early phase of compression. The fuel then evaporates, mixes with the combustion air, and is typically ignited by a spark plug. Engines using this principle generally operate with low to moderate compression ratios, ranging from 8.5:1 to 14:1, with slightly lower ratios in turbocharged engines.

Both methanol and ammonia present unique challenges due to their high enthalpy of evaporation and the need for higher fuel flow rates because of their low specific heating values. This necessitates carefully optimized fuel preparation systems, both in the intake manifold and within the cylinder [7]. Additionally, their properties place significant demands on ignition systems, particularly at lower engine loads.

3.1.1 Monofuel concepts

When marine engines are converted to methanol monofuel concepts, they are often based on gas engines equipped with a methanol port fuel injector in the intake manifold. The compression ratio is adjusted to meet the requirements of the Otto combustion process. Optimized ignition systems are necessary to reliably ignite the fuel and air mixture. In methanol applications, ignition is typically achieved using a spark ignition system.

While monofuel PTX-fuel engines may not achieve the same power density as high-performance diesel engines, they provide a viable solution for applications where full dual-fuel operation, such as a diesel backup, is not required. At the moment these concepts for methanol are restricted to small Highspeed engines and possible future applications.

Ammonia based Otto-concepts use gas valves in the intake manifold and admix ammonia to already existing methane-fuel. Studies use hydrogen to support the homogeneous combustion process or advanced combustion concepts.

3.1.2 Dual Fuel concepts

Marine engines are typically converted to dual-fuel configurations based on turbocharged diesel engines, which operate with high compression ratios (14:1 to 16:1). These high compression ratios significantly limit the use of premixed PTX-fuels. Depending on the extent of modifications made to the original diesel engine, fuel replacement rates of 40% to 70% can be achieved within specific areas of the engine's operating range.

With advanced engine technologies—such as variable valve timing, variable compression ratios, improved heat management, or variable turbocharging systems—higher replacement rates can be achieved. However, it is unlikely that such an engine could maintain the original diesel power output across the entire operating range in full dual-fuel mode. Currently, replacement rates of approximately 60% can be reached with a reasonable level of effort in adapting flexible engine components.

3.2 Heterogeneous Diesel-combustion

Recently developed high-pressure dual-fuel injection systems enable the combustion of methanol and ammonia in a manner closely resembling the classic Diesel combustion process. With these systems, sustainable fuels are injected at high pressures (300 to 700 bar) directly into the highly compressed and hot combustion air near top dead center (TDC). However, because both ammonia and methanol have self-ignition temperatures that are too high, a small amount of diesel is injected beforehand as a pilot fuel to initiate the diffusive combustion of the sustainable fuel spray cones.

These engines achieve a very high power-density, comparable to that of high-performance Diesel engines, as they are not subject to the limitations of misfiring or knocking commonly seen in Otto combustion systems. In operation, they exhibit Diesel-like behavior across nearly the entire engine map. The fuel replacement rate is typically high (around 95%), allowing the engine to operate in almost full dual-fuel mode, ranging from 100% diesel fuel to approximately 95% PTX-fuel. Additionally, the fuel efficiency of high-pressure dual-fuel engines remains close to diesel efficiency over a wide range of operating conditions.

However, there are some challenges associated with high-pressure dual-fuel systems. The injectors required for these systems are highly complex, which is a prerequisite to integrate them into compact four-stroke engines. Furthermore, generating the necessary high pressures is particularly challenging with sustainable fuels, as their physical properties—such as energy density, low viscosity, poor lubrication (tribology), and susceptibility to cavitation—are not well-suited for traditional diesel high-pressure fuel pumps.

On the other hand, with careful engineering of the injection system, components designed for methanol can often be adapted for ammonia with minimal modifications. This simplifies the process of developing engine families capable of using one of the two sustainable fuels.

4 SYSTEM ARCHITECTURE HPDF

The development of high-pressure dual-fuel combustion systems using multi-fuel, multi-needle-nozzle injectors dates back more than 30 years. The first application of this technology was in Wärtsilä Gas-Diesel engines, which operate on the diesel combustion principle. In these engines, pressurized gas at 350 bar is injected using a nozzle with three Gas-needles. The Gas is ignited by a pilot Diesel-fuel nozzle controlled by a mechanical injection valve located at the center of the injector. The three gas needles were actuated by a solenoid-operated hydraulic control valve to open and close the needles [8].

The first use of a similar multi-needle injector concept for liquid fuels was on a Wärtsilä ZA40 engine, which was converted to run on methanol for the Stena Germanica [9]. A similar concept was developed and industrialized by Woodward for the first large-scale serial production of methanol engines for the medium-speed engine segment (Figure 1, 4-needle Multifuel Injector).

In parallel, Woodward began work in 2014 on an advanced combined gas-diesel injector concept for high-speed applications using the gas-diesel combustion process (Figure 1). Over the years, results and insights from this system have been shared in various publications [10].

In 2021, Woodward initiated the development of its High-Pressure Dual-Fuel (HPDF) platform, which was officially introduced at CIMAC World Congress 2023 [11]. Since then, the injector platform's concept and design have been refined and enhanced to align with the overall system architecture of an HPDF system (Figure 1). Additionally, the portfolio has been expanded with the introduction of a new pump concept specifically designed for sustainable fuels.

4.1 HPDF Injector

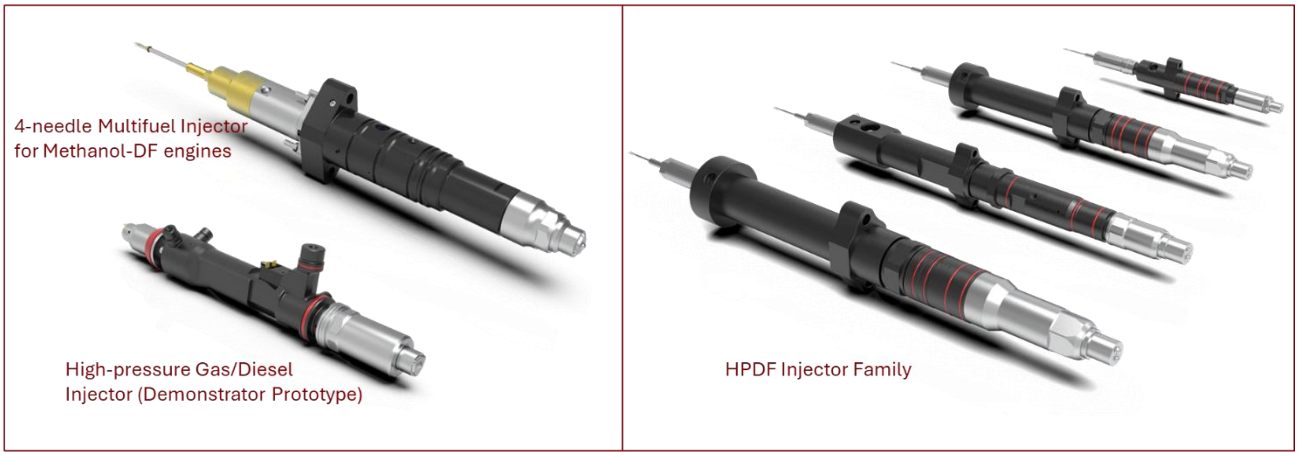

Figure 1. Woodward L'Orange High-Pressure Multifuel Injectors

4.1.1 High-Pressure Dual-Fuel Injector Design and Platform Concept

The high-pressure dual-fuel injector is an advanced system that integrates two independent injectors — a solenoid-actuated PTX-fuel injector and a diesel-fuel injector—within a single casing. Depending on the engine architecture, the diesel injector can either utilize a conventional Pump-Line-Nozzle (PLN) system (Figure 2, left) or an electronically controlled solenoid-actuated Common Rail (CR) system (Figure 2, right). In this context relevant parameters of existing PLN systems of the corresponding Diesel-engines are implemented into the design to assure best engine performance and reduce combustion development effort.

To meet performance stability and durability requirements and manage space constraints, internal accumulators for PTX-fuels and/or diesel fuel (for CR) may be included. These accumulators help dampen pressure oscillations and maintain stable injection pressures.

4.1.2 Combined Nozzle Design for Dual-Fuel Operation

Both injectors share a single nozzle body, enabling a centralized injection and combustion pattern for both diesel and PTX-fuel operation as shown in figure 3. In PTX-fuel mode, the diesel-fuel pilot flame is injected into the same area as the PTX-fuel spray, ensuring reliable ignition and controlled combustion of the PTX-fuel. Careful design of the spray hole positions and angles in the nozzle’s central region allows the diesel-fuel spray and the PTX-fuel spray patterns to intersect effectively. Adjustments to spray hole distances and inclinations help prevent contact with needle domes to assure long lifetime of the nozzle and optimize the interaction between individual spray cones.

This design is especially critical for slow-burning fuels like ammonia. Investigations confirmed that with proper nozzle design, all PTX jets ignite with minimal delay, even for ammonia. These findings led to the adoption of a simplified 1:1 needle concept (Figure 3), replacing the more complex 3:1 needle arrangement as described in the introduction of this chapter. The simpler design retains reliable combustion performance while reducing system complexity.

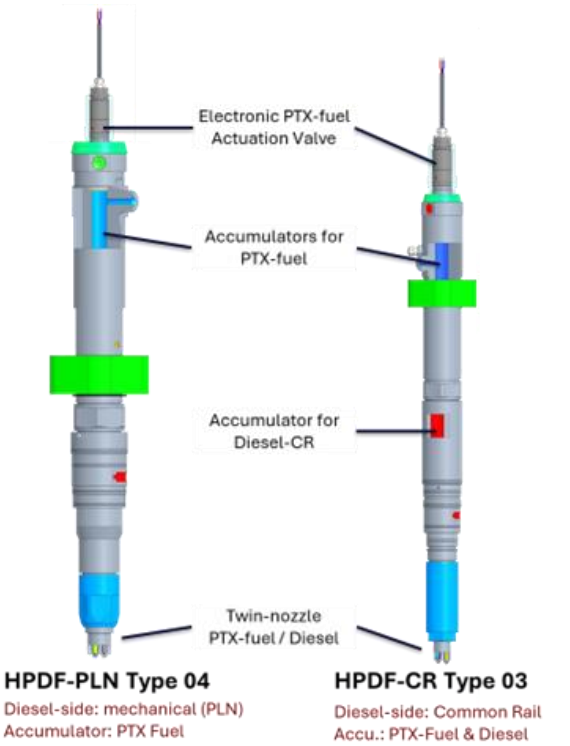

Figure 2. Overview of HPDF-injector concept

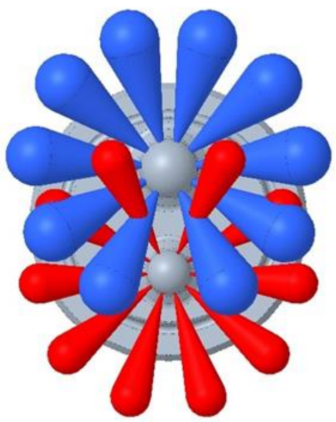

Figure 3. Twin-nozzle design and spray interaction between Diesel and PTX-fuel

4.1.3 PTX Needle Operation and Sealing Mechanism

The PTX needle is hydraulically actuated by a solenoid-driven valve, using either engine oil or diesel fuel as the control fluid, depending on the engine architecture. If diesel fuel is used, leakage is returned to the tank via a return line, while engine oil can be spilled into the upper cylinder head area.

To prevent PTX-fuel from leaking into the diesel fuel system or the control fluid, a sealing oil system is used. This sealing oil is maintained at a slightly higher pressure than the PTX-fuel, ensuring no cross-contamination. Additionally, the pressure difference helps control oil flow into the PTX-fuel system, minimizing leakage while providing lubrication to support the tribological system at the needle-nozzle contact points, as shown in Figure 4.

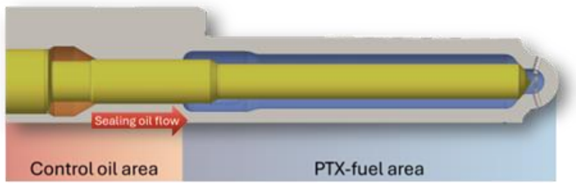

Figure 4. Nozzle sealing concept PTX-needle

4.1.4 Injector Platform Design and Modular Adaptation

The injector platform is designed for flexibility, using validated components and technologies across different size classes. This modular approach allows quick adaptation to different engine designs with minimized validation risks. Internal or external accumulator sizes can also be customized to meet specific engine requirements and space constraints.

A key feature of the platform is a set of predefined nozzle types. Initially, seven nozzle types were developed to cover engine sizes ranging from approximately 100 kW/cylinder to 1,300 kW/cylinder. Each nozzle type is defined by a set of parameters which are kept unchanged across the whole range of the platform. During the concept phase, the two largest nozzle types were excluded to simplify the design and reduce complexity. This decision streamlined the hydraulic control valve design, allowing the entire range of injection quantities to be managed by a single control valve with two flow settings. Further optimization of “Nozzle Type 4” increased its flow capacity, eliminating the need for “Nozzle Type 5.”

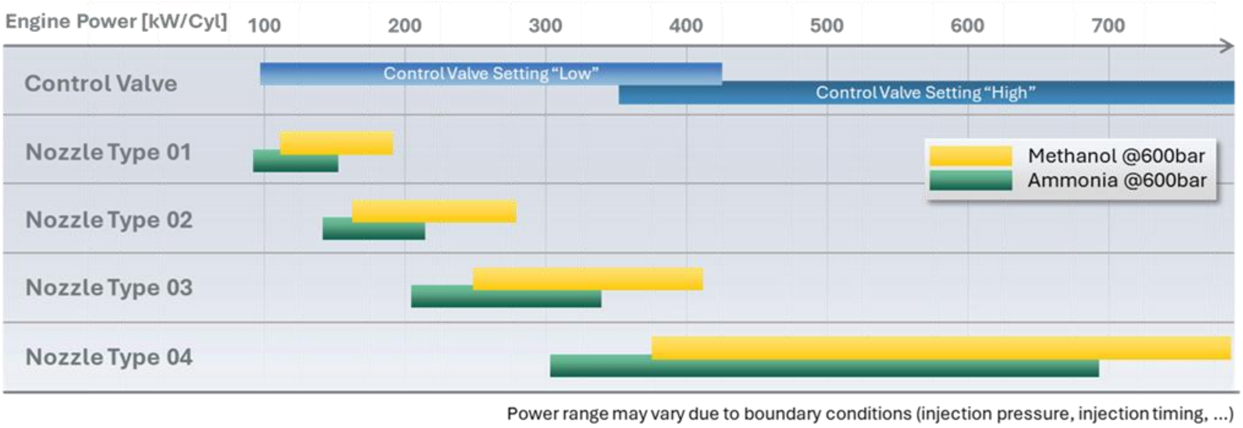

Figure 5. Overview Platform Concept - Nozzle Types & Control Valve

4.1.5 Current Platform Implementation

As implemented today, the platform includes four nozzle types and two control valve settings, covering engine sizes from approximately 100 kW/cylinder to 750 kW/cylinder for methanol (calculated at 600 bar injection pressure) and slightly lower power outputs for ammonia. Figure 5 illustrates the current platform concept, which provides a flexible, scalable solution for dual-fuel injection systems in a wide range of engine applications.

4.2 PTX-Fuel Pump

4.2.1 Status Quo

The choice of PTX-fuel pump that provides constant high pressure to the HPDF injectors, plays a critical role in determining the overall cost of a PTX-fueled propulsion system.

For low-pressure applications, options such as diaphragm pumps, side-channel pumps, and gear pumps are suitable choices due to their ability to handle moderate operating pressures and flow rates. However, when it comes to high-pressure applications, particularly those involving low-viscosity fuels like methanol or ammonia, these pump types face significant limitations in terms of performance and durability. In such cases, piston pumps emerge as the only viable solution, offering the necessary pressure capabilities and robustness required to handle the unique challenges posed by these fuels [12].

Diesel common-rail pumps, widely used in marine engines, are engine-driven piston-pumps operated at high rotational speeds. They use suction-valve-controlled flow regulation to maintain precise fuel delivery, making them compact and highly integrated with the engine.

In contrast, PTX-fuels like methanol and ammonia introduce significant technical challenges that make the use of standard diesel common rail pump technology impractical for these applications. Such challenges are:

- Low Viscosity: PTX-fuels have much lower viscosity compared to diesel, making it harder to achieve effective piston sealing and increasing wear on components.
- Cavitation behavior: Due to their higher vapor pressure, larger vaporization enthalpy, and, in some cases, higher fluid stiffness, PTX-fuels are far more prone to cavitation, leading to significant damage in high-pressure pump systems.
- Flow Control: fuel metering units on the suction side for flow control as used in diesel CR pumps leads to cavitation in PTX systems. Instead, speed-control of the piston, supplemented by pressure control valves on the discharge side to regulate transient conditions are needed for ammonia or methanol.

Given these challenges, the current standard for PTX-fueled four-stroke medium-speed marine engines involves external fuel rigs with slow-moving piston pumps driven by electric motors, a configuration widely used in the process industry.

The use of external fuel rigs is further necessitated by safety and classification regulations. Methanol's high flammability and ammonia's toxicity and corrosiveness require strict measures to mitigate risks of fire, explosion, and health hazards. Classification rules mandate that high-pressure fuel-handling equipment must be located in a separate fuel preparation room, isolated from the engine room. Furthermore, high-pressure methanol or ammonia must be transported to the engine using double-walled pipes to prevent leaks, contain vapors, and protect against accidental releases (figure 6, upper illustration). Flexible elements, such as vibration compensators, are also required to absorb engine vibrations and ensure the durability of the high-pressure lines.

The combination of pump positioning, double-walled piping, and vibration-dampening elements significantly increases the cost of PTX-fuel systems compared to traditional diesel systems. In diesel engines, high-pressure pumps are typically integrated directly into the engine, minimizing the need for external infrastructure. By contrast, the separation of PTX pumps into a dedicated fuel preparation room results in longer and more complex fuel lines, with the mandatory use of double-walled piping adding further material and installation costs. These factors, combined with the need for additional vibration compensators and safety measures, make PTX-fuel systems much more expensive and complex than their diesel counterparts.

4.2.2 New Concepts for PTX-Fuel Pump Integration

To address these challenges and reduce the cost and complexity of current systems, Woodward is developing an advanced pump system concept aimed at integrating high-pressure PTX-fuel generation directly onto the engine.

The proposed concept, as shown in Figure 6, lower illustration, uses an external hydraulic oil rig (hydraulic power unit) operating at pressures between 100 and 200 bar with non-flammable oil as the working fluid. High-pressure PTX-fuel is then generated on the engine using an electronically controlled piston pressure amplifier with integrated safety features to meet classification requirements. This design reduces cost by enabling the use of low-pressure piping from fuel tank to the engine (but still in a double-walled configuration required by classification rules) and enhances system efficiency by centralizing fuel generation.

4.2.3 High-Pressure Pump Family Design

At the core of this concept is a modular pump-family design, as illustrated in Figure 7. The system features an amplification unit with adjustable parameters, including the number of pistons, piston diameter, stroke, and arrangement (e.g., in-line or boxer configuration). These design elements can be tailored to meet the specific needs of various engine architectures.

For engines with access to a mechanical drive for the hydraulic pump, the oil rig functionality can also be integrated directly onto the engine, further reducing costs and complexity. This modular approach ensures flexibility while leveraging validated components to minimize development risks and enable quick adaptation to different engine sizes.

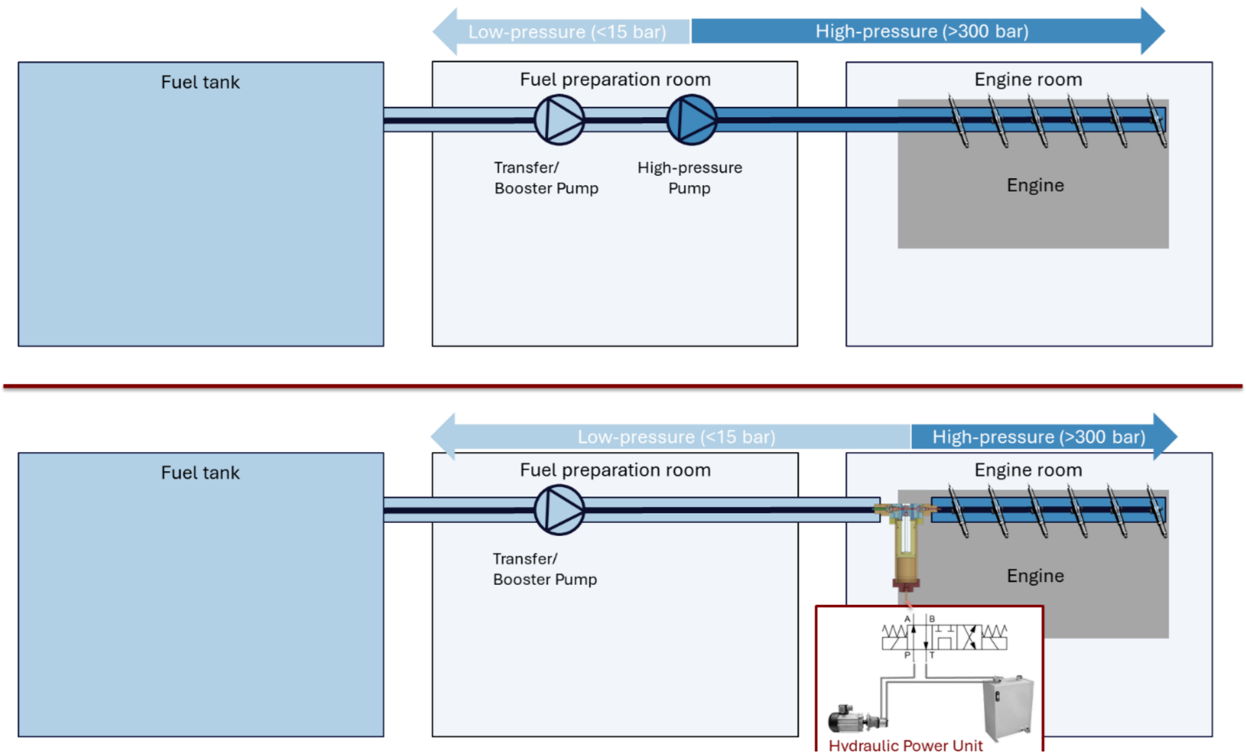

Figure 6. High pressure system concepts

By integrating PTX-fuel generation onto the engine, Woodward's concept addresses the technical and regulatory challenges associated with PTX-fuels while offering a more cost-effective and streamlined alternative to traditional external pump rigs

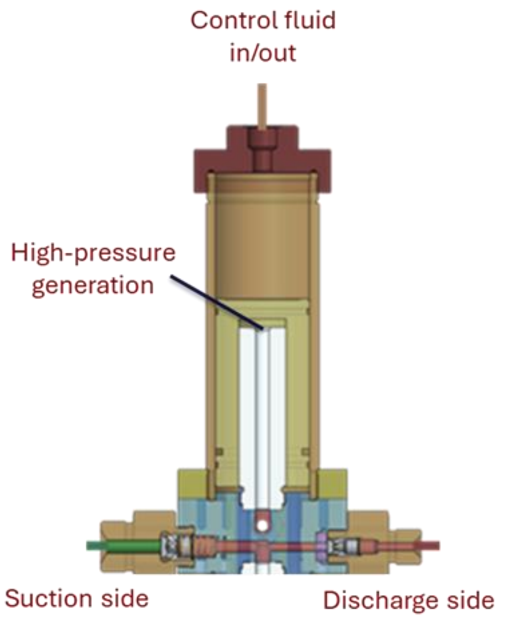

Figure 7. Compact pressure amplifier unit

5 PURGING SYSTEM ARCHITECTURE

To extend the lifespan and maintain the safety of the PTX-fuel injection system, it is essential to purge the system. This step is typically performed either before switching to diesel-only operation or prior to shutting down the engine completely.

Figure 8 provides a simplified diagram of the PTX-fuel injection system in PTX-fuel mode, including an integrated purging mechanism. While the actual system design is often more complex and tailored to specific customer requirements, this illustration highlights the key components for clarity. The system features a nitrogen accumulator and a system purge valve (SPV).

Figure 8 illustrates the system during PTX-fuel operation. In this mode, fuel is transferred from the PTX-fuel tank to the high-pressure pump (HPP), and then fed via the high-pressure fuel lines to the injectors. During this operation, the SPV remains closed.

The purging process in figure 9 begins with purging of the high-pressure pump (HPP) and the high-pressure fuel lines. During this phase, most of the PTX-fuel is redirected to a separator and returned to the PTX-fuel tank.

As a next step, the injectors are purged during operation of the engine in diesel-mode. The PTX-side of the HPDF injector is energized to inject remaining PTX-fuel. This occurs during the intake stroke to reduce the required nitrogen pressure as much as possible (Figure 10). Residual PTX-fuel is distributed into the combustion chamber, where it is burned in combination with 50–75% diesel fuel in the subsequent combustion cycle. This is repeated for a subsequent period of injections, depending on the injector and system size to ensure thorough purging of the injection system and to minimizes residual PTX-fuel. A repetition of this complete cycle after a few minutes removes any remaining liquid-phase PTX-fuel that may have accumulated during the initial purge.

Full purging of the injection system is crucial to prevent corrosion, both during continued diesel operation and after the engine is shut down. By effectively removing PTX-fuel residues, the purging process safeguards the system against damage, ensuring stable performance over time.

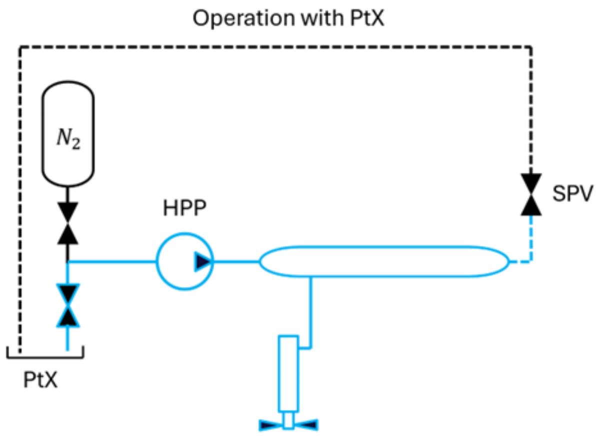

Figure 8. PTX-fuel system: PTX-fuel mode

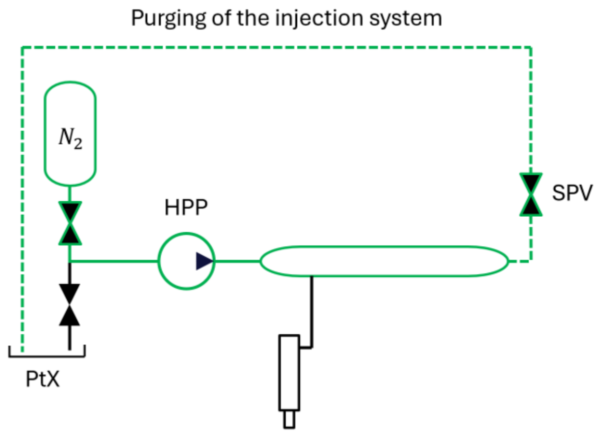

Figure 9. PTX-fuel system: system-purging

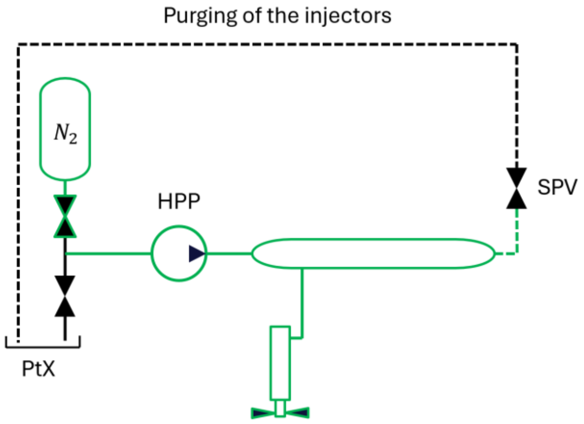

Figure 10. PTX-fuel system: injector-purging

6 PRACTICAL IMPLEMENTATION AND VALIDATION

6.1 Platform-Validation

Compared to traditional diesel fuel systems, PTX-fuel injection systems are relatively new and face significant technical challenges, as outlined earlier. While some insights can be drawn from high-pressure LNG Gas-Diesel (GD) systems used in the past, these experiences are limited. Additional knowledge has been gained from early adaptations of GD systems modified for methanol operation in initial applications. However, these legacy systems were not designed with the unique demands of PTX-fuels in mind.

The goal of platform development is to fundamentally rethink existing concepts and create a family of injectors and pumps that can accommodate a wide range of engine designs. This approach aims to meet the fast-paced demands of the ongoing energy transition by enabling a short time-to-market while ensuring reliability and performance.

A robust validation process supports this development effort. The corrosive properties of methanol, for example, require advanced material development that goes far beyond the standard practices for material selection in diesel fuel systems. This additional level of material innovation ensures that PTX-fuel injection components can withstand the harsh conditions presented by methanol and other sustainable fuels, providing long-term durability and functionality across various applications.

6.1.1 Basic material development

Injection system components experience exceptionally high mechanical stresses, necessitating meticulous design optimization to reduce stress concentrations in critical areas. To ensure durability, production processes must be fine-tuned to manufacture complex geometries with smooth, stress-resistant surfaces. Additionally, materials used in these components require targeted hardening, especially in high-impact regions like needle seats, which endure the highest mechanical loads.

The corrosive properties of methanol add another layer of complexity to the design process. To address this, developers must conduct thorough durability testing in methanol-rich environments to assess and validate material performance under these challenging conditions.

Insertion Tests for Material Screening

Insertion tests are a crucial first step in selecting materials suitable for use in methanol-fuel environments. During these tests, material probes—prepared with their final heat treatments and surface finishes—are exposed to methanol fuel in both liquid and gaseous state. The tests are conducted under varying temperatures and fuel compositions, with particular attention to the effects of water and salt concentrations, which significantly influence the corrosive behavior of the material surfaces. A typical setup is shown in figure 11 with probes inserted into the methanol-fuel environment. The different probes then are exposed to elevated temperatures for several weeks.

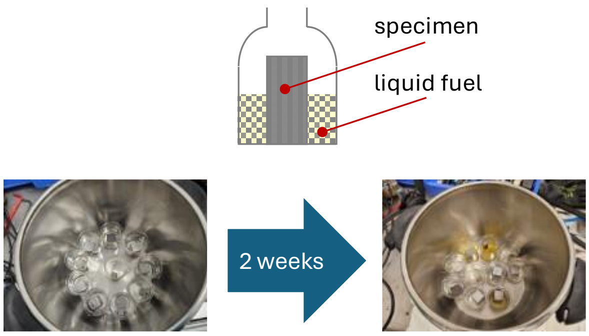

Figure 11. Insertion tests setup

The primary results of these tests are obtained through visual inspections of the material surfaces. These inspections assess the presence and extent of corrosion products formed during the test period, providing an initial indication of material degradation and potential loss over time. Materials deemed suitable for further consideration should exhibit no visible signs of corrosion, as exemplified in Figure 12.

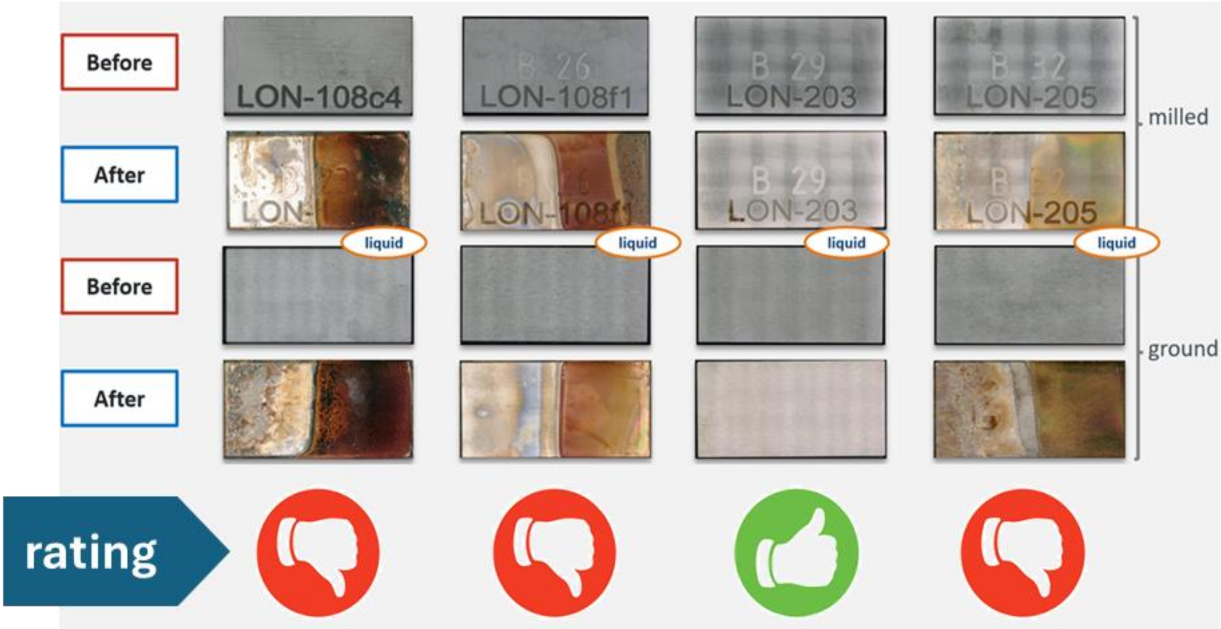

Figure 12. Visual surface assessment after insertion tests

Following this initial, somewhat subjective evaluation of material resistance, the most promising material samples undergo detailed analysis using Scanning Electron Microscopy (SEM). This step allows for the identification of intergranular corrosion, which is particularly concerning as it can serve as a precursor to crack initiation in components subjected to high mechanical loads. For samples showing signs of intergranular corrosion in the methanol gas phase as shown in figure 13, further analysis is required to determine the depth and propagation of cracks,

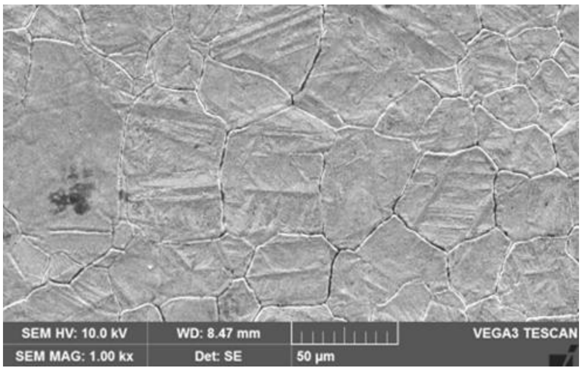

Figure 13. Intergranular corrosion after insertion test

ensuring the material's suitability for high-stress applications.

Fatigue Tests in Methanol-fuel Environments

Insertion tests provide early evidence that materials exposed to methanol environments, particularly those containing water or salt admixtures, are susceptible to chemical attack. As a result, fatigue testing for materials used in methanol injection systems must be conducted under methanol-specific conditions to accurately evaluate their performance in injection systems.

To address this need, a specialized test setup as shown in figure 14 was developed at the WTZ Rosslau Research Center. This setup allows for the analysis of various materials under expected fuel compositions and operating conditions, ensuring a comprehensive evaluation of their behavior under cyclic stress, which is relevant for injection components.

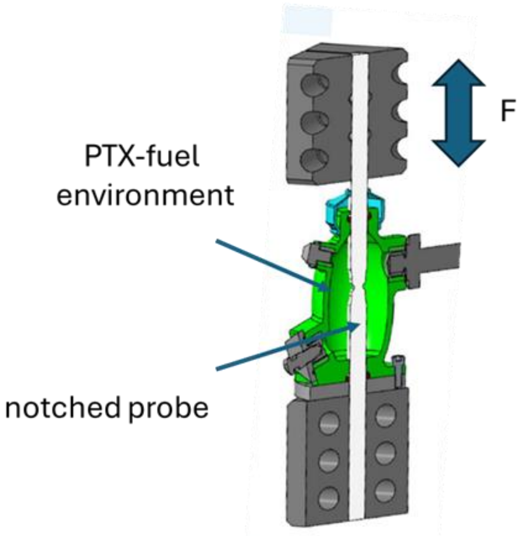

Figure 14. Fatigue testing in methanol environment

One of the key findings from these tests, illustrated in Figure 15, is the significant difference in material durability between operation in air and in methanol-fuel environments. The results show that, depending on the material and the specific methanol composition, a substantially shorter lifespan is observed under cyclic stress when methanol-fuel is present.
These findings highlight the critical importance of optimizing component design to account for the reduced durability in methanol-fuel environments. Stress levels must be minimized by design optimization and safety factors increased, to ensure the long-term reliability and performance of the materials used in methanol injection systems.

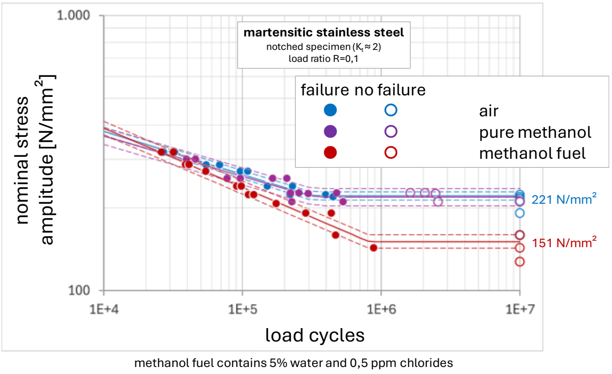

Figure 15. Wöhler-curve for materials in air and different methanol-fuel compositions

6.1.2 Methanol test rigs

Woodward L'Orange is in the final stages of constructing a cutting-edge test rig for methanol fuel systems, with commissioning scheduled in the coming weeks (Figure 16). Designed to meet ATEX regulations, the rig will enable comprehensive endurance testing of high-pressure dual-fuel (HPDF) injectors and PTX-fuel pumps under realistic conditions. The primary focus will be on analyzing wear mechanisms, cavitation effects, and long-term durability, addressing the unique challenges posed by methanol's low viscosity and high vapor pressure. This will allow early identification of critical failure modes, ensuring faster and more efficient development cycles.

In parallel, hydraulic investigations for methanol systems are already being conducted on existing common rail test benches. Using substitute fluids with viscosity properties close to methanol, these tests provide valuable insights into injection quality, including pressure dynamics, injection rate shaping, and cavitation behavior.

Additionally, engine testing with methanol is ongoing, further contributing to a deeper understanding of system performance and durability under real-world operating conditions and especially with effects form combustion.

Once operational, the methanol test rig will complement these efforts by enabling closed-loop, non-combustion testing of real methanol fuel. This advanced facility, alongside the ongoing engine and hydraulic testing, will form a robust validation framework, accelerating the development of reliable, high-performance methanol fuel systems to support the maritime industry's transition to sustainable fuels.

6.2 Validation strategy and status

Validation strategy of the HPDF injection platform follows a similar modular approach as the platform design itself. First, a detailed analysis was conducted for each functional module to determine potential failure modes or wear mechanisms that lead to a premature failure or a deterioration of the performance using well-known Failure Mode and Effects Analysis (FMEA). Second, a validation strategy was defined for each identified critical failure mode, distinguishing between:

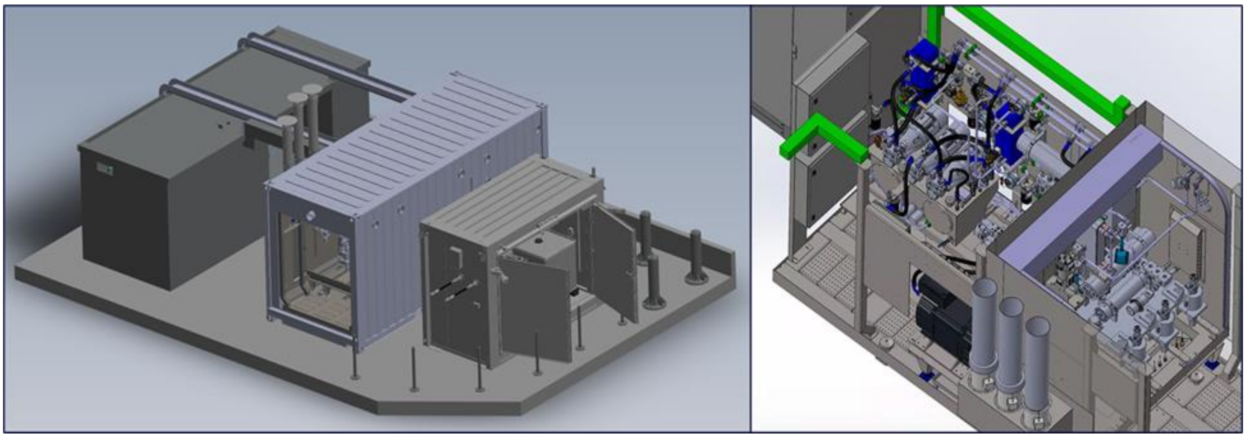

Figure 16. Methanol test rig (middle container) with control room and fuel tank (left / right container) and view of the testing architecture

- validation on module or component level
- validation with full injector on a component test rig with testing oil
- validation with full injector on a component test rig running with methanol
- validation with full injector on a customer lab engine

Finally, as a third step, it was also defined if each identified failure mode can be validated for the whole platform, for one injector size, or for every individual application.

Validation on module level, injector level and lab engine level are ongoing. The validation status of the different injector sizes, fuel types and diesel-side injection technologies are depicted in figure17.

The HPDF injector platform demonstrates a scalable and flexible approach to PTX-fuel and full Diesel-fuel operation. Its modular design supports a wide range of engine applications, while the integration of advanced multi-fuel nozzles ensures precise and efficient combustion of both diesel and PTX-fuels. Similarly, the development of PTX-fuel pumps has focused on overcoming the technical challenges associated with low-viscosity and cavitation-prone fuels, ensuring stable high-pressure fuel delivery. Together, these systems form the backbone of future-ready marine engines capable of operating with sustainable fuels.

The continued development and optimization of fuel systems will be a cornerstone of the industry's decarbonization efforts. Key priorities include:

	Diesel Side: Pump-Line-Nozzle (PLN)		Diesel Side: Common Rail (CR)	
	Methanol	Ammonia	Methanol	Ammonia
Injector Type 01	No market demand expected	No market demand expected	Concept in progress	No market demand expected
Injector Type 02	Design implemented Lab Eng. testing 2025	Design implementation in progress	Concept in progress	Market demand unclear
Injector Type 03	Lab Engine Testing in progress. TAT completed	Lab Engine Testing in progress. TAT completed	Design implementation in progress	Concept in progress
Injector Type 04	Lab Engine Testing in progress	Design completed Lab Eng. testing 2025	Design implementation in progress	Concept in progress

Figure 17. Development status of HPDF Injector Family

The PTX pump family is currently being tested in an early prototype stage with the focus on sealing concepts and control algorithms. The definition of the whole platform in terms of offered sizes is ongoing, considering market demand of different engine segments, engine integration constraints and system cost.

7 CONCLUSION AND OUTLOOK

The adoption of sustainable fuels such as methanol and ammonia marks a critical milestone in the decarbonization of the shipping industry. This paper has highlighted the central role of advanced fuel systems—particularly the Woodward High-Pressure Dual-Fuel (HPDF) injector platform and PTX-fuel pump—in addressing the unique challenges posed by these sustainable fuels. Through modular designs, material innovation, and rigorous validation processes, these systems are enabling the use of PTX-fuels in marine 4-stroke engines while ensuring reliability, adaptability, and performance under demanding conditions.

- Cost Reduction: Simplifying system architectures, such as integrating PTX-fuel pumps directly onto engines, and employing advanced manufacturing techniques will be essential to reduce costs and bridge the gap between PTX and diesel systems. Modular designs that allow scalability across different engine sizes will further improve cost efficiency.
- Validation and Testing: Extensive validation remains crucial to ensure the reliability and durability of HPDF injectors and PTX pumps. This includes material testing in methanol and ammonia environments, durability testing to combat wear and corrosion, and system-level validation to refine performance under real-world operating conditions. Validation strategies must continue to evolve to address the increasing complexity of new fuel systems.

Broader Industry Considerations for Decarbonization

Beyond fuel systems, several additional factors are pivotal for the shipping industry to successfully transition to sustainable operations:

- Fuel Supply Infrastructure: The widespread adoption of methanol and ammonia depends on the availability of a reliable global supply chain, including production, storage, and distribution networks tailored to these fuels.
- Advanced Combustion Strategies: Research into optimized combustion processes, such as improved spray dynamics and ignition systems, will drive further advancements in fuel efficiency and engine performance for sustainable fuels.
- Digitalization and Predictive Maintenance: The integration of digital technologies, such as real-time monitoring, data-driven diagnostics, and predictive maintenance systems, will help improve operational efficiency, extend the lifespan of critical components, and reduce downtime.
- Regulatory Alignment and Incentives: Collaboration with regulatory bodies will remain vital to establish clear, harmonized standards that promote innovation while ensuring safety and reliability. Incentives for retrofitting existing fleets and adopting sustainable technologies will accelerate the transition.

In conclusion, the HPDF injector platform and PTX-fuel pump represent the technological foundation for integrating sustainable fuels into marine engines. However, for the industry to achieve full decarbonization, these advancements must be complemented by broader efforts in fuel infrastructure, digitalization, and regulatory support. By addressing both the technical and systemic challenges, the shipping industry can successfully navigate the path toward a cleaner, more sustainable future.

8 ACKNOWLEDGMENTS

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