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Further development of a methanol port fuel injection platform for medium-speed engines

Fuel Injection & Gas Admission and Engine Components

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ABSTRACT

Methanol is gaining increasing importance as a promising alternative to fossil fuels. With a relatively high energy density and better handling compared with other low carbon fuels, methanol represents a particularly interesting option. Additionally, methanol is favored by advanced regulatory frameworks available that simplify its introduction as a fuel. The rapid development of production capacities for sustainable methanol gives market participants confidence in its future availability. Market instruments, such as the EU Emissions Trading System, are expected to further enhance the competitiveness of methanol against conventional fuels. All these factors highlight methanol's attractiveness as a fuel, and the growing number of methanol-powered ships further confirms this trend.

A key prerequisite for the encouraging outlook described above is the development of the necessary technologies that enable efficient operation and minimal CAPEX expenditures. Many OEMs and suppliers are working intensively on engine development, optimization of combustion processes, and the development of associated components. Injection systems are undoubtedly one of the crucial building blocks for methanol-powered engines and are therefore a focus for almost all engine manufacturers. In addition to suitability for engine newbuilds, the ability to retrofit existing engines plays an even more important role. The need to decarbonize already operating ships requires solutions that can be implemented relatively easily, without compromising performance and cost-effectively in the field.

In 2021, Heinzmann launched the world's first port fuel injection (PFI) methanol injector for medium-speed engines. The PFI technology applied for methanol injection has proven to be a powerful, flexible, and cost-effective solution in numerous projects. The experience gained from several hundred injectors in the field has also revealed further development areas. A central aspect of this development lies in spray targeting. A fine atomization and a precise form of the spray in the intake manifold is crucial for efficient combustion, minimizing emissions, and preventing undesirable effects from incomplete fuel evaporation entering the combustion chamber or depositing on the intake walls. The work was focused on nozzles optimisation and structures to specifically shape the spray geometry. Various designs were tested to find the balance between droplet size, spray angle, and penetration depth. Material compatibility was another essential consideration due to methanol's corrosive properties. Testing special materials and coatings has ensured injector longevity, which is vital for the technology's practical applicability and acceptance. Extensive bench and field tests confirmed the injectors' durability under various load and temperature conditions. All the previous development steps have culminated in a methanol injectors platform design that offers a lineup capable of addressing a broad range of engine bore sizes and power per cylinder.

In the paper, we are going to discuss the methodology and results of the Heinzmann PFI methanol injector platform's further development. The achieved results so far and ongoing field tests underscore this technology's potential, suggesting its broader application in medium and high-speed engines.

1 INTRODUCTION

The need to reduce, or ideally eliminate, greenhouse gas emissions that contribute to climate change is now a widely acknowledged priority. While individuals are encouraged to limit their carbon footprint, it is imperative for governments worldwide to implement policies that drive the development of sustainable technological solutions across nearly every sector of human activity.

Internal combustion engines (ICE) have long been recognized as a critical factor in the energy transition process. While they are indispensable for numerous daily applications -such as transportation of people and goods, as well as energy generation- they also pose significant environmental concerns. These concerns stem from their high emissions of carbon dioxide (CO_2), nitrogen oxides (NO_x), particulate matter (PM), and unburned hydrocarbons (uHC), particularly when powered by fossil fuels.

To address these challenges, the transition to alternative, low-carbon fuels has become a priority in both industrial and academic research. Among the various alternatives, methanol stands out as a particularly promising candidate. Compared to other options such as ammonia or hydrogen, methanol offers a unique combination of advantages:

- Ease of storage and handling: Unlike hydrogen, which requires cryogenic temperatures or high-pressure tanks for storage, methanol is liquid under ambient conditions. This simplifies its integration into existing fuel storage and distribution infrastructures [1].
- Lower toxicity and operational risks: Compared to ammonia, methanol is less toxic and safer to handle, making it a more practical choice in many industrial applications [2].
- Renewable production pathways: Methanol can be produced sustainably from a variety of feedstocks, including biomass, waste carbon dioxide, and renewable electricity, enhancing its potential as a circular and green fuel [3].
- Combustion characteristics: Methanol burns cleanly with lower emissions of particulate matter and nitrogen oxides compared to conventional fossil fuels, making it particularly attractive for applications where emission control is critical [4].

The maritime industry, responsible for approximately 3% of global greenhouse gas emissions, is one of the sectors most actively exploring methanol as an alternative fuel. With the International Maritime Organization (IMO) setting ambitious targets to reduce emissions to reach net-zero GHG emissions from international shipping by or around, i.e. close to, 2050, ship operators and engine manufacturers are under pressure to adopt cleaner technologies [5].

Methanol's compatibility with internal combustion engines, coupled with its relatively high energy density and ability to blend with other fuels, makes it an ideal candidate for maritime applications [6]. Furthermore, the possibility of retrofitting existing marine engines to operate on methanol presents a cost-effective pathway for reducing emissions without requiring entirely new fleets.

Methanol can be introduced into the engine using either direct injection (DI) or port fuel injection (PFI) systems. While direct injection offers advantages in terms of combustion efficiency and power output [7], it requires higher system complexity and precise engineering to handle the high pressures and challenging conditions associated with methanol's physical properties. In contrast, port fuel injection is a simpler and more cost-effective solution, as it operates at lower pressures and involves fewer advanced components. This simplicity makes PFI particularly attractive for retrofitting existing engines, offering a more accessible pathway for adopting methanol with reduced initial investment and system maintenance costs [8].

Moreover, by focusing on scalable solutions that can be tailored to diverse engine platforms and power requirements, fuel injection technology developers play a pivotal role in reducing emissions and making methanol adoption more accessible and economically viable. The close collaboration between injection system developers and engine manufacturers is essential to accelerate the decarbonization of the maritime sector and achieve global sustainability targets.

In this context, HEINZMANN began the development of a PFI methanol injector in 2020, with the initial results presented in a previous study [9]. This paper provides an in-depth exploration of the deflector technology utilized in the injector, detailing its critical role in spray formation and the scalability of this technology for engines with varying power per cylinder. Additionally, it highlights the development of a flow limiter, integrated as a key safety feature of the HEINZMANN methanol injection system. Finally, the paper addresses the upcoming challenges, including material compatibility with methanol and wear resistance, which are crucial for ensuring long-term performance and reliability of both the injector and the flow.

2 INNOVATIVE DEFLECTOR DESIGN FOR METHANOL INJECTION SYSTEMS

The HEINZMANN methanol injector (Fig. 1) is a straightforward servo valve equipped with a single-hole nozzle. At the nozzle outlet, an impingement surface -hereafter referred to as “the deflector”- serves as the core technology of the injector. This surface directs the methanol flow and generates high shear forces, which break the surface tension of the liquid, initiating the formation of droplets. The deflector also shapes the fluid flow into a fine spray pattern, ensuring optimal fuel atomization for efficient combustion

Figure 1. HEINZMANN Methanol Injector with the deflector

The deflector, integrated within the impingement surface, plays a pivotal role in adapting the injector to the specific characteristics of methanol and its operational conditions:

- High Shear Forces for Droplet Formation: The deflector generates high shear forces necessary to overcome the surface tension of methanol, particularly considering the unique properties of the fuel such as its low viscosity, high latent heat of vaporization, and relatively high surface tension compared to conventional fuels. These forces are crucial for initiating droplet formation, enabling atomization even at low pressures and high flow rates.

- Flow Shaping and Fine Spray Generation: As the methanol jet impinges on the deflector surface, the deflector shapes the flow, transforming it into a finely atomized spray. This is especially important given the high fuel flow rate (> 4.000 mm³ per shot) and low available pressure (< 100 bar, specifically in this case < 25 bar) within the injector. Despite these challenging conditions, the deflector ensures the generation of a fine mist of methanol, which is essential for achieving the desired combustion efficiency.

In the below sequence of images (Fig. 2 to 4), the evolution of the methanol jet and the influence of the deflector technology are clearly demonstrated.

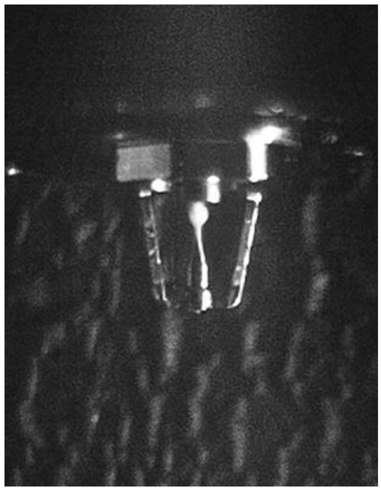

Figure 2. Methanol jet exiting the nozzle

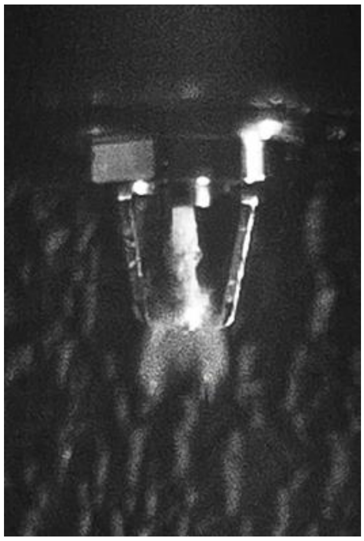

Figure 3. Initial deflector interaction, showing radial dispersion

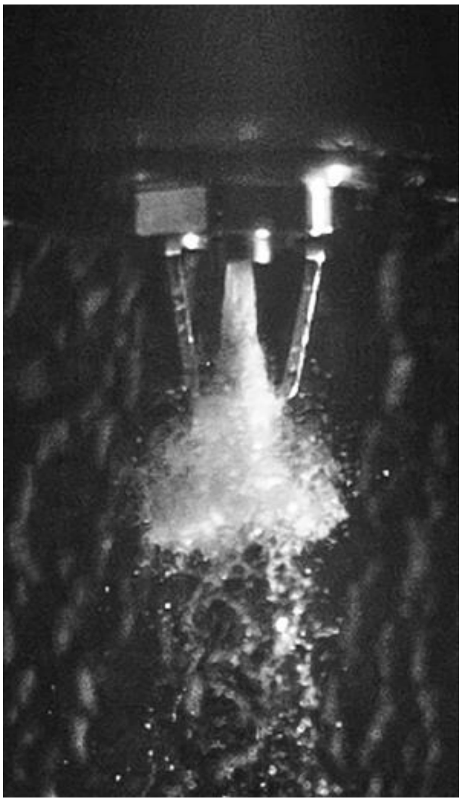

Figure 4. Fully developed spray, with uniform atomization

In Fig. 2, the methanol jet exits the nozzle as a concentrated and narrow stream, indicating a flow with minimal interaction or disturbance. This initial pattern shows a focused trajectory and limited spray dispersion.

Fig. 3 illustrates the beginning of the jet's interaction with the deflector cone. As the jet impinges on the deflector, it starts to spread radially, forming a more distributed spray pattern. This redirection and breakup of the fuel stream are facilitated by the deflector's geometry, which induces controlled turbulence.

At last, Fig. 4 captures the full impact of the deflector on the methanol jet. The spray has now transformed into a wide, uniform cloud of fine droplets, demonstrating efficient atomization. This dispersion ensures better fuel-air mixing, which is essential for achieving optimal combustion efficiency in methanol-powered applications.

The sequence highlights the capability of the deflector technology to modify the spray pattern dynamically. This adaptability not only enhances injector performance but also makes the design highly scalable and versatile, allowing for tailored configurations based on specific combustion requirements.

By leveraging the deflector’s capability to adapt to these demanding parameters low pressure, high flow rate, and the physical properties of methanol, the injector achieves efficient atomization, making it an ideal solution for utilizing methanol as an alternative fuel in internal combustion engines.

2.1 Geometric design of the deflector (beam splitter)

The deflector in the HEINZMANN methanol injector is designed with a conical shape (see Fig. 5), which plays a critical role in optimizing fluid dynamics for efficient atomization. This conical geometry is carefully shaped to direct the methanol flow and enhance droplet formation. The deflector's form is tailored to handle the unique physical properties of methanol, such as its surface tension, as well as the specific operational conditions of the injector, including high fuel flow rates and low injection pressures.

Figure 5. HEINZMANN deflector technology

The deflector is typically structured as a cone with its apex aligned with the nozzle outlet. This conical shape ensures that the methanol jet impinges on the surface at the correct angle, which is essential for effective atomization. The cone’s rotational symmetry further guarantees a uniform distribution of shear forces across the methanol flow.

The deflector angle, or the opening angle of the cone, is a key parameter in controlling the spray pattern. Depending on the application and the required spray characteristics, the angle can vary, typically ranging from 20° to 60°. This angle is critical in balancing the formation of fine droplets and ensuring proper fuel distribution within the combustion chamber.

Moreover, the deflector’s geometry shapes the methanol flow into a fine spray by forcing the fluid to accelerate and break into smaller droplets. This process minimizes turbulence and maximizes atomization efficiency. The surface of the deflector is designed to provide a smooth transition for the fuel, optimizing the flow dynamics and enhancing the overall atomization process.

Finally, the geometry of the deflector is adjustable to accommodate different engine types and performance requirements. Modifications in the deflector's angle and surface finish enable the injector to be fine-tuned for specific combustion conditions, ensuring that methanol is atomized effectively, even under varying pressures and flow rates.

2.2 Deflector Supports and Structural Design

The deflector is supported by a robust and symmetrical structure designed to ensure stability and precision during operation (Fig. 6).

Figure 6. Deflector supports (complete assembly)

The key components of the support structure include:

- Radial supports: Three radial support elements connect the deflector cone to the outer structure, arranged at 120° intervals to ensure symmetrical load distribution and minimize mechanical stress concentration. While this configuration serves as the standard, it can be modified if specific spray requirements necessitate adjustment.

- Outer Frame: The radial supports are fixed to an external frame that serves as a rigid base. This frame ensures the overall integrity of the structure and aligns the deflector cone within the nozzle.

- Assembly: A threaded connection secures the deflector and its supporting components to the nozzle body. This system guarantees precise positioning and resistance to mechanical vibrations during operation.

The combination of these elements creates a stable support system for the deflector. The open design of the supports minimizes obstruction to the flow, ensuring optimal functionality of the injector while maintaining mechanical reliability under operational stresses. Designing this support posed challenges, as it needed to be thin enough to avoid disrupting the spray pattern and droplet formation while remaining robust enough to withstand the mechanical stresses from the methanol jet, intake manifold temperatures, and engine vibrations.

The robust yet minimally invasive design of the radial supports ensures stability without compromising functionality. Anchored by a cone connected to the nozzle, the deflector system remains securely in place, preventing misalignment that could impact atomization. This configuration allows the deflector to generate high shear forces and shape the fuel spray, even under challenging conditions like low pressure and high flow rates. The structure combines durability with precision, maintaining optimal spray formation essential for efficient combustion and reduced emissions.

To evaluate the structural integrity and performance of the deflector support, a Finite Element Analysis (FEA) and a fatigue analysis were conducted. Fatigue analysis predicts the durability of a component under repeated or cyclic loads. It assesses how material responds to stresses that, though not causing immediate failure, can lead to microcracks and eventual failure over time.

For a methanol injector, this analysis helps estimate the number of cycles the component can withstand before failure, ensuring reliable performance. The results are typically presented as S-N curves, which correlate stress amplitude with the number of cycles to failure, crucial for ensuring the component's longevity in dynamic environments like internal combustion engines.

Exploiting the symmetry of the support structure, only one-third of it was simulated (see Fig. 7), with the applied forces scaled appropriately to account for the symmetry.

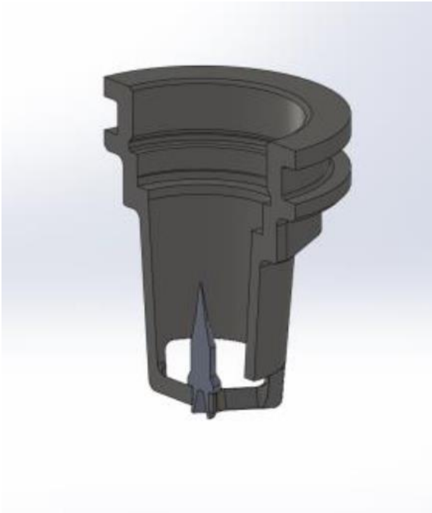

Figure 7. Model of the support and deflector used for simulation

It has been assumed that the injector operates by injecting methanol at 15 bar through fixed-diameter nozzle. The resulting fluid flow applies forces to the deflector, which in turn induces mechanical stress on the support. This stress was evaluated using FEA in ANSYS Mechanical (2022 R2), with boundary conditions derived from Computational Fluid Dynamics (CFD) simulations or equivalent methods. The methanol flow during injection was initially modeled in Simcenter Amesim (LMS Amesim, Siemens Digital Industries Software) to estimate flow-induced forces, providing a preliminary understanding of the system's loading. These estimates were validated through further simulations in ANSYS Fluent to precisely determine the maximum forces. While the calculated forces may slightly exceed actual values due to the exclusion of flow losses (e.g., friction), the analysis provides a conservative basis for design.

Both the FEA and fatigue analyses adhered to the FKM guidelines [10], evaluating the structural integrity under static and cyclic loading conditions. Two safety factors were calculated: the first, called static safety factor SF_{static}, evaluates the resistance to failure under static loading, while the second, fatigue safety factor SF_{fatigue}, assesses the component's resistance to fatigue failure under cyclic loading.

The analyses identified two critical regions (see Fig. 8):

- Domain A: Connection points of the radial support to the deflector, experiencing tensile stress primarily due to bending forces.
- Domain B: Connection points of the radial support to the deflector, subjected to compressive stress resulting from contact forces at the deflector support interface.

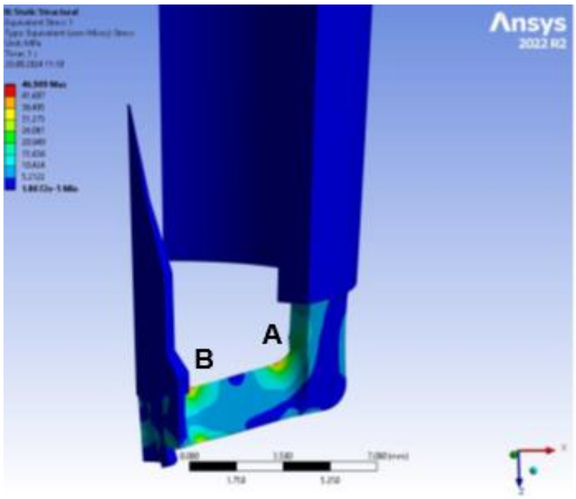

Figure 8. Critical domains A and B

The safety factors were calculated as follow:

$$SF_{\mathrm{static}} = \frac{\sigma_{\mathrm{y}}}{\sigma_{\mathrm{applied}}} \qquad (2.2.1)$$

Where:

- σ_{y} is the yield strength of material, indicating the maximum stress that can be applied before plastic deformation occurs.
- $\sigma_{\mathrm{applied}}$ is the highest stress experienced by the component during static load.

$$SF_{\mathrm{fatigue}} = \frac{\sigma_{\mathrm{N}}}{\sigma_{\mathrm{a}}} \qquad (2.2.2)$$

Where:

- σ_{N} is fatigue strength at a specified number of cycles (N). This parameter reflects the maximum stress amplitude that a material can endure for a given number of loading cycles without experiencing failure. The values for σ_N are derived from S-N curves, which are essential for understanding material behavior under cyclic loading.
- σ_{a} is stress amplitude defined as the difference between the maximum and minimum stresses experienced by component during each loading cycle divided by 2.

The S-N curve and the corresponding parameters for fatigue analysis were determined in accordance with the FKM guideline. The S-N curve defines the relationship between stress amplitude and the number of cycles to failure, incorporating material properties, surface conditions, and stress concentration factors as specified by the FKM standard. These parameters are critical for accurately predicting the fatigue life and ensuring the structural reliability of components under cyclic loading conditions.

The fatigue strength of the component at both points exceeded the material fatigue limit, with safety factors of 8.8 at domain A and 10 at domain B. Fig. 9 and Fig. 10 show the S-N curves for the critical regions.

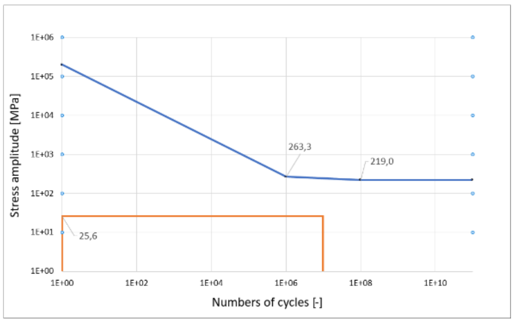

Figure 9. S-N curve of domain A

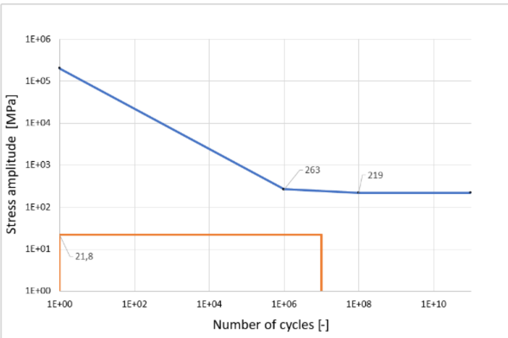

Figure 10. S-N curve of domain B

Two distinct regions are visible in the curve: the finite life region, where the permissible stress amplitude decreases with increasing cycles, and the endurance limit, where the stress amplitude stabilizes at 219 MPa beyond 10^6 cycles, indicating that the material can theoretically endure infinite cycles without failure.

The analysis parameters, calculated according to FKM, include a mean stress of 23.7 MPa for domain A and -23.8 MPa for domain B, a stress amplitude of 23.7 MPa for domain A and 23.8 MPa for domain B, and a stress amplitude of 25.6 MPa for a fully reversed cycle (R= -1) for domain A and 21.8 MPa for domain B. The material fatigue strength is 208 MPa for both domains A and B, while the component fatigue strength, corresponding to 10^6 cycles, is almost 263 MPa for domains A and B. The endurance limit amplitude is 219 MPa for both domains, below which the material can operate indefinitely without fatigue failure. The safety factor, calculated as 8.6 for domain A and 10 for domain B, indicates that the design stress is significantly lower than the critical fatigue stress, ensuring a conservative and reliable design.

These results, obtained using the FKM standard, highlight the material's high fatigue strength and endurance limit, making it suitable for applications requiring long-term resistance to cyclic loading. The incorporation of a large safety factor demonstrates a conservative design approach, ensuring operational safety and reliability under the calculated conditions. This analysis confirms the robustness of the material and component design for high-fatigue applications, following the rigorous and validated methodologies outlined in the FKM guidelines.

3 SCALABILITY OF THE METHANOL INJECTOR AND THE DEFLECTOR TECHNOLOGY

The innovative design of the deflector, as detailed in the previous chapters, demonstrates a unique combination of aerodynamic efficiency and mechanical robustness. This design is not only optimized for the specific requirements of methanol as a fuel but is also inherently scalable, making it adaptable to a wide range of engine displacements.

Such scalability is crucial for applications in the maritime sector, where engines range from small auxiliary units to large-scale propulsion systems. The deflector's ability to maintain efficient atomization and spray formation across varying fuel flow rates and injection pressures ensures that it can meet the demands of diverse engine sizes without compromising on performance or durability.

In this chapter, we will explore how the deflector design has been successfully adapted to different engine displacements, highlighting its modularity and flexibility. This includes modifications to the deflector geometry and support structure to accommodate varying power requirements while maintaining the high efficiency and reliability of the injection system.

Currently, HEINZMANN offers up to five different configurations of deflector geometries and nozzle diameters, tailored to cover a wide range of engine power outputs. These configurations enable the injection system to serve engines with power outputs ranging from 100 kW per cylinder to approximately 500 kW per cylinder.

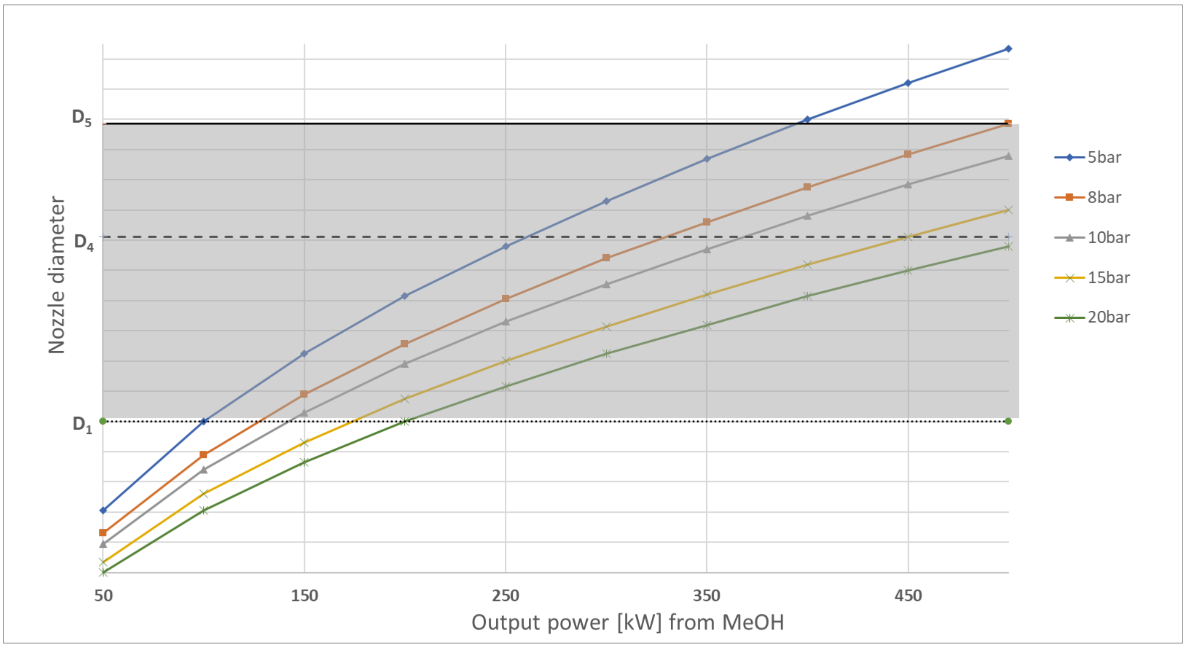

Figure 11. Nozzle diameter for MeOH power fraction per cylinder

The graph in Fig. 11 illustrates the power ranges achievable with the injector as a function of different available nozzle diameters (from D_1 to D_5, where D_1 is the smallest). The five curves represent varying methanol supply pressures upstream. The shaded gray area indicates the effective operating range, where the injector can function reliably. Portions of the curves outside this area are purely theoretical, as the real injector cannot operate in those conditions.

This flexibility is achieved while operating within a pressure range of 5 to 20 bar, making the injector suitable for both low- and medium-pressure applications. The adaptability of the deflector's design ensures that even with varying fuel flow rates and engine sizes, efficient atomization and optimal spray formation are consistently maintained.

By offering multiple deflector and nozzle configurations, HEINZMANN addresses the diverse requirements of internal combustion engines in different industrial and maritime applications. This modular approach minimizes the need for extensive redesigns while maximizing performance across a broad spectrum of operational conditions.

Figures 12 and 13 demonstrate how the design and fundamental geometry of the deflector are consistently maintained across configurations, regardless of the target power output. However, for deflectors designed for higher power ranges, the impingement surface area of the deflector is significantly increased. This enlargement extends the interaction time between the methanol flow and the deflector, enabling better flow guidance and enhancing the spray quality of the increased fuel volume.

Figure 12. Deflector geometry for small power output

Figure 13. Deflector geometry for big power output

The optimized design ensures that even at higher flow rates, the spray is finely atomized and evenly distributed, meeting the stringent combustion efficiency and emissions reduction requirements.

4 FLOW LIMITER: A CRITICAL SAFETY COMPONENT FOR THE INJECTION SYSTEM

In methanol injection systems, maintaining a consistent and controlled fuel flow is crucial for both performance and safety. To mitigate the risk of excessive fuel delivery that could potentially damage the injector or other engine components, HEINZMANN has developed a flow limiter. This component can be easily integrated with the PF injector, ensuring enhanced control over the fuel flow without compromising the functionality of the injector itself. This safety feature serves to regulate the maximum flow rate of methanol, preventing over-injection that could result in mechanical failure or inefficient combustion. Studies have shown that managing the flow within precise limits enhances both system reliability and combustion efficiency ([11], [12]).

The flow limiter operates by controlling, or in this specific case by limiting, the fuel supply under various operating conditions, particularly at higher fuel pressures, ensuring that the injector performs within its designated parameters. This is particularly crucial in applications where precise fuel atomization is essential for achieving optimal combustion and emission reduction. The integration of such components has been recognized as a key advancement in optimizing performance and reducing wear in high-performance injectors.

Although flow limiter valves are not inherently innovative components in injection systems, the challenges faced and overcome during the development of this component were significant. Not only was the use of methanol as the fuel medium a key challenge, but also the need to minimize pressure drop across the flow limiter. Ensuring a minimal drop in pressure is crucial to maintaining the highest possible pressure upstream of the injector, thus preventing any detrimental effects on spray generation. The design of the flow limiter has been optimized to maintain consistent fuel flow while preserving the injector's performance in terms of atomization, which is essential for efficient combustion and emission control.

The flow limiter developed by HEINZMANN (as single component in Fig. 14, connected with the methanol injector in Fig. 15) is a normally open valve featuring a piston, a spring, and an orifice plate. The differential pressure generated across the orifice plate counteracts the spring force. When the delivered volume exceeds 200% of the nominal value, the differential pressure becomes sufficient to fully compress the spring, causing the valve to close and stopping any further flow.

Figure 14. HEINZMANN flow limiter

Figure 15. HEINZMANN methanol injector with the integrated flow limiter

4.1 Development and 1D Simulations of the Flow Limiter

The valve design was developed using 1D simulations conducted in Amesim. These simulations evaluated various diameters of the orifice plate while keeping the spring constant k fixed. The objective was to verify that the flow limiter functioned as intended under the boundary conditions defined by methanol upstream pressures of 16 and 10 bar and temperatures of 20 °C and 60 °C. These two conditions will be indicated as: Q_1 the delivered volume at 16 bar and 60 °C, Q_2 the delivered volume at 10 bar and 20 °C. It was assumed that if the valve performed correctly under these two conditions, it would function effectively across all intermediate flow scenarios. This systematic approach allowed for the identification of an optimal orifice plate diameter that ensures precise control of the flow limiter across the entire operating range.

The primary design goals for the flow limiter were twofold: first, to ensure that the valve remains open until 200% of the nominal delivered volume $Q_{nominal}$ is reached, and second, to guarantee that the valve returns to its initial open position before the start of the next injection event. For this purpose, 1D simulations in Amesim were carried out, exploring various orifice plate diameters Ø while maintaining a fixed spring constant.

The simulation results are presented in Figures 16–17, showing the valve's behavior under different orifice plate diameters. The key parameters analyzed were:

1. Return to Initial Position: The ability of the valve to reopen fully before the start of the next injection event, which was defined to occur within a crank angle of much less than 720°, ensuring timely operation of the injection cycle.
2. Closing delivered volume: The injected quantity at which the valve fully closes, ideally around 200% of the $Q_{nominal}$.

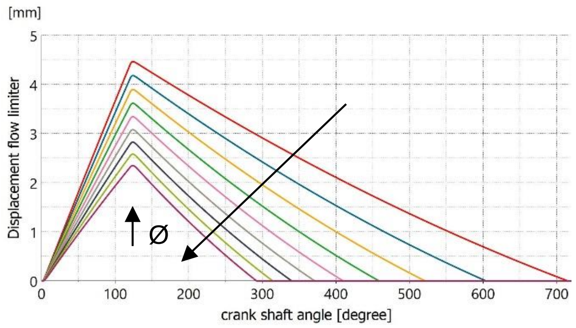

Figure 16. Piston Displacement [mm] vs. engine crank angle [°] at fixed *k*

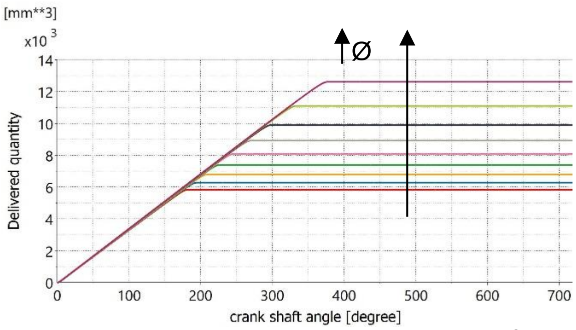

Figure 17. Valve closing delivered volume [mm^3] vs. engine crank angle [°] at fixed *k*

The graphs reveal a broad range of orifice diameters that can meet these requirements, each with distinct trade-offs in terms of flow dynamics, response time, and pressure stability. The HEINZMANN development team carefully evaluated these options, considering both theoretical performance and practical manufacturability. The final selection was made based on an educated guess, leveraging extensive experience and balancing optimal flow control, structural integrity, and ease of integration into the injector system.

Based on the simulation data, the orifice plate diameter was selected to achieve the desired performance. The optimal diameter ensures that the valve closes at the target flow rate and reliably returns to its initial position within the required time frame. This ensures both system protection and seamless operation during repeated injection cycles.

After selecting the orifice diameter, the behavior of the complete flow limiter-injector system was simulated. The objective was to ensure that the piston within the flow limiter valve returned to its fully open initial position after each injection cycle, even after multiple cycles. Additionally, it was crucial to verify that, under the two extreme flow conditions - Q_1 and Q_2 - the valve would reliably close at around 200% of $Q_{nominal}$ in the event of an injector malfunction, such as remaining unintentionally open.

Figure 18 illustrates the dynamic response of the flow limiter-injector system during two consecutive injection cycles. The red curve represents the needle lift of the methanol injector, indicating the activation and deactivation of the injection event. The blue curve shows the differential pressure ($p_2 - p_1$) across the orifice, which directly influences the operation of the flow limiter. The yellow curve displays the volume of methanol transferred through the flow limiter during each cycle, while the green curve represents the displacement of the piston within the flow limiter valve.

These simulations confirm the proper functioning of the system. The displacement (green curve) demonstrates consistent behavior, returning to its fully open initial position before the start of the next injection cycle.

It is also particularly interesting to analyse the differential pressure across the orifice plate (blue curve), which is a key parameter for controlling the piston movement within the valve. Initially, when the injector (red curve) activates, the fuel flow increases, resulting in a rise in differential pressure.

As methanol flows through the orifice, the differential pressure (blue curve) reaches a peak, which reflects the moment when the flow limiter is regulating the flow rate. This pressure difference counteracts the spring force within the valve, moving the piston (green curve) toward the closed position.

Once the injector needle closes, the flow rate decreases, leading to a rapid drop in differential pressure. This allows the spring to push the piston back to its fully open position. The consistent return of the pressure profile to baseline values between injection cycles ensures that the system resets correctly, avoiding cumulative errors or delays in the flow limiter's response

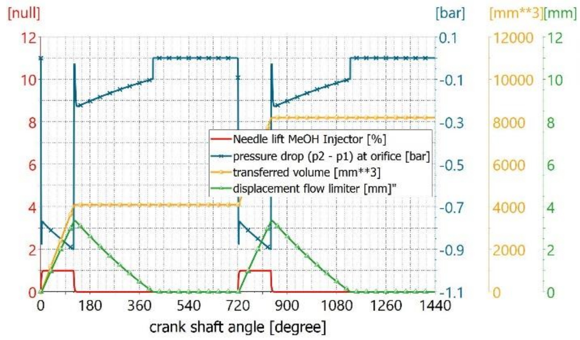

Figure 18. Dynamic response of the flow limiter during two consecutive injection cycles

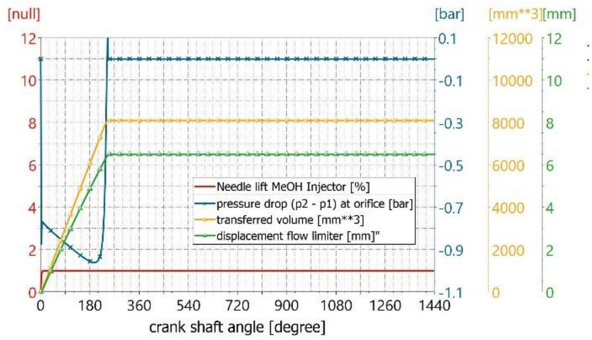

Figure 19. Flow limiter’s performance @ Q_1

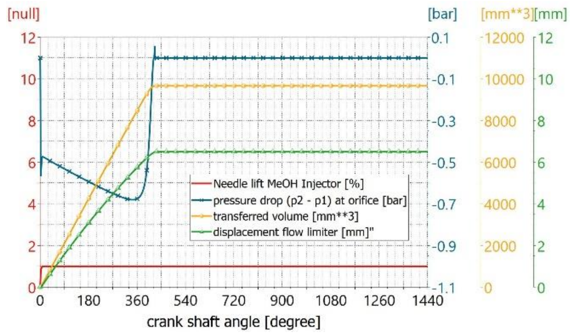

Figure 20. Flow limiter’s performance @ Q_2

The graphs in Fig. 19 and in Fig. 20 illustrate the flow limiter’s performance under the two extreme flow conditions: Q_1 and Q_2. In both cases, the red curve (needle lift) indicates the injector activation, while the blue curve (pressure drop across the orifice) shows the expected pressure response during the injection cycles. The yellow curve (transferred methanol volume) represents the methanol flow passing through the limiter, and the green curve (piston displacement) confirms that the piston reliably closes at approximately 200% of $Q_{nominal}$ in both scenarios. Moreover, the simulations demonstrate that the piston returns to its fully open position before the subsequent injection event, validating the theoretical proper operation of the flow limiter across both flow limits.

Based on the simulation data, three different orifice diameters were selected for further investigation. These diameters were manufactured and tested on a dedicated test bench to validate the simulation results and ensure that the flow limiter performs as expected under real operating conditions.

4.2 Validation of Simulation Results Through Functional Testing

The validation of the simulation results was carried out through functional testing, performed at an external test facility. The primary objective was to verify the functionality of the flow limiter system, particularly its closing behaviour, and to optimize its parameters where necessary. This included adjustments to the orifice diameter and the spring force to ensure the proper functioning of the injector system under both nominal and extreme operating conditions.

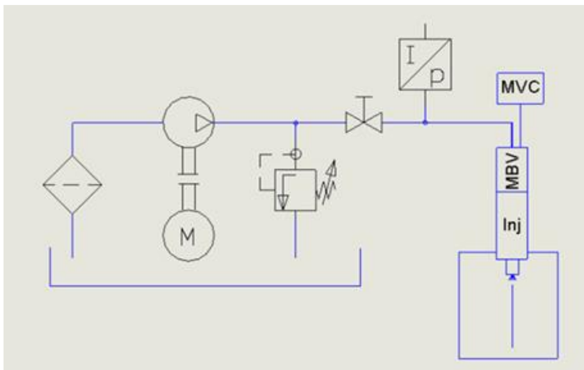

Figure 21. Hydraulic scheme of the test bench

The hydraulic schematic of the test bench is shown in Figure 21. The setup was designed to simulate real operating conditions and evaluate the performance of the injector and flow limiter system. Methanol-compatible pressure generation equipment supplied the injectors and the flow limiter. A pressure tank was employed to maintain consistent conditions during the measurements. The injection is controlled by the HEINZMANN ECU, called Magnetic Valve Control (MVC).

For injection quantity measurement, a tank equipped with a mounting flange tailored to the injector was used. The tank also incorporated isobaric balloons to ensure consistent internal pressure. During the test, a specified number of injections were collected in the tank. The tank and its mounting setup were weighed before and after the test. The weight difference divided by the number of injections yielded the quantity of methanol injected per cycle.

Several calibration steps were performed to refine the system's performance:

- The orifice diameter was optimized through drilling and reaming to achieve precise flow rates.

- Springs of varying stiffness were tested and replaced to adjust the closing force and ensure reliable operation.

This iterative process aimed to achieve an optimal opening characteristic for the flow limiter while maintaining stability against oscillations and ensuring robust performance

Three different orifice diameters were tested under identical conditions to determine the optimal configuration. The results showed that the orifice diameter of approximately 3 mm provided the best performance.

The flow limiter operated effectively within a pressure range of 10 to 15 bar, with no functional limitations observed. At 8 bar, the 3 mm orifice diameter still functioned, but performance became less stable and reproducible.

The flow limiter consistently closed at the target flow rate of 200% of the nominal value and reopened after a pressure reduction of approximately 2 bar.

Over multiple injections at a nominal flow rate of 200% of the nominal value, the flow limiter showed no unintended closures and maintained consistent operation.

The pressure drop across the flow limiter was approximately 1 bar, which closely matched the simulation predictions. This pressure drop accounts for the roughly 6% reduction in the actual flow rate compared to the theoretical injector calculations, with minimal deviation when this adjustment is factored in.

Based on these results, the orifice diameter of 3 mm was selected as the optimal configuration for further testing and implementation. It should be noted that this selection was specifically determined for this particular configuration, including the given pressure and injector flow rate. Future tests will focus on long-term durability once hardened components are available.

5 MATERIAL COMPATIBILITY AND FUTURE CHALLENGES

In this chapter, we delve into the critical topic of material compatibility in the context of methanol injector development, alongside the challenges faced and the solutions implemented. Building on earlier discussions of the deflector technology for achieving the desired spray formation, the static and fatigue resistance verified through the FEA, and the development and validation of the flow limiter through bench testing, we now shift focus to the materials themselves.

The development process faced several challenges, particularly concerning material compatibility with methanol and meeting the functional requirements of the injector. The materials needed to satisfy stringent operational criteria based on their specific purposes. One of the primary concerns was impact resistance, as moving parts within the injector that interacted or collided with each other required materials with high impact resistance to ensure durability under repeated use. Additionally, some components relied on specific magnetic properties to effectively perform their roles within the injector system.

Despite meeting these functional requirements, many materials initially considered were not inherently resistant to methanol's corrosive properties or capable of sustaining long-term durability. This necessitated an iterative process to identify and test materials that could balance these often-conflicting requirements. Where it was not feasible to find a material that simultaneously fulfilled all criteria -functional properties, corrosion resistance, and long-term durability- alternative solutions were explored.

During the development of the injector, two main strategies were employed: coatings and surface treatments on the one hand, and design modifications on the other hand.

A key example of surface treatment was the application of a ferritic nitrocarburizing process to improve corrosion resistance. While this treatment provided good corrosion protection, it proved insufficient for long-term durability due to the "egg shell effect," where the treated layer became brittle and prone to cracking over time.

Design modifications were made to adjust the geometries and interfaces of the components to reduce wear and address material limitations. However, this approach carried certain risks. Even minor changes to the geometry of critical components could lead to issues such as cavitation. Cavitation occurs when rapid pressure changes cause vapor bubbles to form and collapse, leading to localized damage on the material's surface. This phenomenon can compromise both the performance and the durability of the injector

By addressing these material challenges, HEINZMANN successfully developed an injector that not only performed as required but also demonstrated long-term reliability in methanol-fueled applications. The lessons learned here underline the importance of a multidisciplinary approach in material selection and design adaptation when dealing with emerging fuel technologies.

Future challenges in material compatibility will likely center on improving sustainability and recyclability without compromising performance. Additionally, further research into novel materials and coatings tailored for methanol applications could yield significant advancements in injector technology and beyond.

6 CONCLUSION

In conclusion, the development of the methanol injector represents a significant advancement in fuel injection systems, offering a high level of flexibility and adaptability. The deflector technology, as detailed throughout the paper, stands out due to its ability to be easily scaled to accommodate a wide range of engine displacements, making the injector suitable for both small auxiliary units and large-scale propulsion systems. This scalability ensures that the injector can maintain optimal performance and durability across various engine sizes, crucial for applications in the maritime sector.

The integration of a flow limiter further enhances the injector's functionality, providing a safety mechanism that ensures precise control over fuel delivery, even in high-pressure conditions. Through the use of simulation and extensive bench testing, the flow limiter's design has been optimized for reliability and efficiency, ensuring that the injector consistently operates within its desired parameters.

The challenges faced during material selection, particularly regarding methanol compatibility, have been successfully addressed through a combination of coatings, surface treatments, and design modifications. These efforts have resulted in an injector that is not only durable but also capable of performing efficiently in demanding methanol-fuelled applications. The iterative process of material testing and design adaptation highlights the importance of a multidisciplinary approach in developing robust technologies for emerging fuel types.

Looking ahead, the continued refinement of materials and the exploration of novel coatings will be key to enhancing the injector's long-term sustainability and performance. The flexibility of the deflector design, combined with the robust flow control system and durable materials, positions this injector as a reliable solution for the evolving demands of methanol-based fuel systems in the maritime sector and beyond

7 REFERENCES AND BIBLIOGRAPHY

[1] Müller, K., Fabisch, F., & Arlt, W. (2014). *Energy Transport and Storage using Methanol as a Carrier. Green, 4(1-6). doi:10.1515/green-2013-0028*

[2] Yadav, O., Valera, H., Dulani, D., Krishnan, U., Agarwal, A.K. (2021). *Safety Aspects of Methanol as Fuel.* In: Agarwal, A.K., Valera, H., Pexa, M., Čedík, J. (eds) Methanol. Energy, Environment, and Sustainability. Springer, Singapore. https://doi.org/10.1007/978-981-16-1280-0_5

[3] Shamsul, N. S., Kamarudin, S. K., Rahman, N. A., & Kofli, N. T. (2014). *An overview on the production of bio-methanol as potential renewable energy.* Renewable and Sustainable Energy Reviews, 33, 578–588. doi:10.1016/j.rser.2014.02.024

[4] Verhelst, S., Turner, J. W., Sileghem, L., & Vancoillie, J. (2019). *Methanol as a fuel for internal combustion engines*. Progress in Energy and Combustion Science, 70, 43–88. doi:10.1016/j.pecs.2018.10.001

[5] International Maritime Organization. (2023). *2023 IMO strategy on reduction of GHG emissions from ships*. International Maritime Organization. https://www.imo.org/en/OurWork/Environment/Pages/2023-IMO-Strategy-on-Reduction-of-GHG-Emissions-from-Ships.aspx

[6] Zincir, B., Deniz, C. (2021). *Methanol as a Fuel for Marine Diesel Engines.* In: Shukla, P.C., Belgiorno, G., Di Blasio, G., Agarwal, A.K. (eds) Alcohol as an Alternative Fuel for Internal Combustion Engines. Energy, Environment, and Sustainability. Springer, Singapore. https://doi.org/10.1007/978-981-16-0931-2_4

[7] Zhu, Z., Xu, L., Duan, H., Wang, Y., Wang, X., Zeng, K., & Wang, Y. (2023). *In-depth comparison of methanol port and direct injection strategies in a methanol/diesel dual fuel engine*. *Fuel Processing*

Technology, 241, 107607. https://doi.org/10.1016/j.fuproc.2022.107607.

[8] Dierickx, J., Verbiest, J., Janvier, T., Peeters, J., Sileghem, L., & Verhelst, S. (2021). Retrofitting a high-speed marine engine to dual-fuel methanol-diesel operation: A comparison of multiple and single point methanol port injection. Fuel Communications, 7, 100010. doi:10.1016/j.jfueco.2021.100010

[9] Sorrentino, A, Leytes, V., Mattheueuws, L., De Wilde, E., "*Methanol port fuel injection for medium speed application: injector development and engine design*", CIMAC 2023

[10] FKM-Richtlinie: Rechnerischer Festigkeitsnachweis für Maschinenbauteile, 6. Ausgabe. VDMA Verlag, 2012

[11] Bai, X.-S., & Im, H. G. (2024). *Performance of a Methanol-Fueled Direct-Injection Compression-Ignition Engine under Low-Temperature Combustion Conditions.* Energies, 17(17), 4307. DOI: 10.3390/en17174307

[12] Yilmaz, A. C., Uludamar, E., & Aydin, K. (2018). *Fuel Efficiency Improvement with Water-Methanol Injection for Internal Combustion Engine.* International Journal of Automotive Engineering and Technologies, 7(4), 139-145.