Comparison of Ammonia High-Pressure Direct Injection and Ammonia Port-Fuel-Injection

Vergleich zwischen Ammoniak Saugrohreinspritzung- und Ammoniak-Hochdruck-Direkteinspritzung

A. Braun[1]*, T. Baufeld[3], S. Bernhardt[1] H. Mohr[2], H. Kubach[1], S. Prehn[4]
[1]Karlsruhe Institute of Technology, Karlsruhe (Germany)
[2]GasKraft Engineering, Beckdorf (Germany),
[3]Liebherr Machines Bulle SA, Bulle (Switzerland)
[4]University of Rostock, Rostock (Germany)
*Corresponding Author: Annalena.braun@kit.edu

Abstract

Ammonia is considered a promising carbon-free fuel for the decarbonization of maritime transport. While most research focuses on ocean shipping, its application in inland waterway transport is gaining importance, particularly as green ammonia is expected to be imported via sea-going vessels and distributed regionally. Within the CAMPFIRE alliance, a propulsion system for inland waterway vessels fueled by renewable ammonia is being developed. A key component of this work is the development and evaluation of efficient ammonia combustion strategies in spark-ignited engines. To investigate suitable combustion concepts, experiments were conducted on a single-cylinder research engine at the Karlsruhe Institute of Technology (KIT), representing the geometry of a future multi-cylinder marine engine. This study focuses on the comparison of ammonia port fuel injection (PFI) and ammonia high pressure direct injection (DI) concepts supported by hydrogen co-fueling. The combustion concepts were systematically evaluated with respect to achievable energetic ammonia share, combustion stability, ignition behavior, efficiency, and emission characteristics.

The results demonstrate that ammonia direct injection significantly improves the stable operating range towards higher energetic ammonia shares in leaner operating conditions. The DI concept showed consistently lower ignition delay and improved combustion stability compared to PFI operation. This behavior is attributed to locally enhanced mixture reactivity near the spark plug caused by preferential hydrogen availability, which promotes reliable flame kernel formation. While DI exhibited longer overall combustion durations due to the subsequent combustion of ammonia-rich zones, the improved early combustion phase resulted in stable heat release and robust engine operation. Efficiency and emission levels of both concepts were found to be comparable over wide operating ranges. Furthermore, the DI concept allows operation with higher hydrogen fractions without inducing knocking, indicating reduced sensitivity to mixture composition fluctuations and improved operational robustness. This is particularly beneficial in ammonia-based fuel systems, where hydrogen is supplied by a cracker and temporary variations in hydrogen yield can occur, as it enhances tolerance to such fluctuations and prevents knock under dynamic operating conditions. The findings highlight ammonia direct injection as a highly promising combustion strategy for future ammonia-fueled marine engines. An outlook is given on the transfer of the combustion concept to a containerized multicylinder-engine demonstrator currently under development.

Kurzfassung

Ammoniak gilt als vielversprechender kohlenstofffreier Kraftstoff für die Dekarbonisierung des Seeverkehrs. Während sich die meisten Forschungsarbeiten auf die Seeschifffahrt konzentrieren, gewinnt seine Anwendung im Binnenschiffsverkehr zunehmend an Bedeutung, insbesondere da grünes Ammoniak voraussichtlich mit Seeschiffen importiert und regional verteilt werden wird. Im Rahmen der CAMPFIRE-Allianz wird ein Antriebssystem für Binnenschiffe entwickelt, das mit erneuerbarem Ammoniak betrieben wird. Ein wichtiger Bestandteil dieser Arbeit ist die Entwicklung und Bewertung effizienter Ammoniakverbrennungsstrategien in Ottomotoren. Um geeignete Verbrennungskonzepte zu untersuchen, wurden am Karlsruher Institut für Technologie (KIT) Versuche an einem Einzylinder-Forschungsmotor durchgeführt, der die Geometrie eines zukünftigen Marine-Vollmotors repräsentiert. Diese Studie konzentriert sich auf den Vergleich von Konzepten zur Ammoniak-Saugrohreinspritzung (PFI) und Ammoniak-Direkteinspritzung (DI) mit Wasserstoff als Zusatzkraftstoff. Die Verbrennungskonzepte wurden systematisch hinsichtlich des erreichbaren energetischen Ammoniakanteils, der Verbrennungsstabilität, des Zündverhaltens, des Wirkungsgrads und der Emissionseigenschaften bewertet.

Die Ergebnisse zeigen, dass die direkte Ammoniak-Einspritzung den stabilen Betriebsbereich deutlich in Richtung höherer Ammoniakanteile unter magereren Betriebsbedingungen verbessert. Das DI-Konzept zeigte im Vergleich zum PFI-Betrieb durchweg eine geringeren Brennverzug und eine verbesserte Verbrennungsstabilität. Dieses Verhalten wird auf die lokal verbesserte Reaktivität des Gemisches in der Nähe der Zündkerze zurückgeführt, die durch die bevorzugte Verfügbarkeit von Wasserstoff verursacht wird und eine zuverlässige Flammenkernbildung fördert. Während DI aufgrund der nachfolgenden Verbrennung ammoniakreicher Zonen insgesamt längere Verbrennungszeiten aufwies, führte die verbesserte frühe Verbrennungsphase zu einer gleichmäßigen Wärmefreisetzung und einem robusten Motorbetrieb. Die Effizienz und die Emissionswerte beider Konzepte erwiesen sich über weite Betriebsbereiche als vergleichbar.

Darüber hinaus ermöglicht das DI-Konzept den Betrieb mit höheren Wasserstoffanteilen ohne Klopfen, was auf eine geringere Empfindlichkeit gegenüber Schwankungen in der Gemischzusammensetzung und eine verbesserte Brennverfahrensrobustheit hindeutet. Die Ergebnisse unterstreichen die Ammoniak-Direkteinspritzung als vielversprechende Verbrennungsstrategie für zukünftige mit Ammoniak betriebene Schiffsmotoren.

1. Introduction

Shipping plays a crucial and largely irreplaceable role in global transportation, particularly with regard to the movement of goods. Due to its high transport efficiency, maritime shipping already represents one of the most climate-efficient modes of transport. Nevertheless, substantial further reductions in greenhouse gas emissions are required to meet long-term sustainability targets. While battery-electric propulsion offers a viable pathway toward climate-neutral mobility in road transport, its applicability to maritime applications is severely limited by insufficient energy density. For most vessel types and operating profiles, alternative solutions for storing and supplying renewable energy on board are therefore required [1]. In this context, hydrogen produced from renewable sources represents a promising energy carrier. However, the low volumetric energy density of elemental hydrogen, whether stored in compressed or liquefied form, poses significant challenges for maritime use. One approach to overcoming these limitations is the conversion of hydrogen into liquid energy carriers [2]. Synthetic hydrocarbons produced via processes such as Fischer–Tropsch synthesis are attractive due to their compatibility with existing engine technologies. However, their large-scale production relies on the availability of concentrated carbon sources. Without extensive deployment of energy-intensive and costly direct air capture technologies, the limited availability of CO_2 represents a major constraint on production capacity, thereby restricting widespread application [3]. Ammonia offers an alternative pathway by enabling hydrogen storage without the need for carbon [4]. It can be synthesized from hydrogen and abundantly available nitrogen and has therefore gained increasing attention as an energy carrier for maritime applications. Owing to its established global infrastructure for production, storage, and transport, ammonia is particularly attractive for shipping. Ammonia can be used directly as a fuel in internal combustion engines. However, its unfavorable combustion characteristics, including high auto ignition temperature and low laminar flame speed, present challenges, especially for medium- and high-speed engines [5]. These limitations can be mitigated by the addition of a small amount of hydrogen to promote ignition and stabilize combustion. Such hydrogen can be supplied by decomposing a fraction of the onboard ammonia in a dedicated cracking unit upstream of the engine [6]. The successful implementation of this concept requires careful system integration and optimization of the interaction between fuel processing and engine operation. This paper discusses the application of ammonia-based combustion concepts for inland waterway vessels, focusing on recent developments in ammonia port fuel injection and ammonia high-pressure direct injection, combustion process design, and system integration.

2. System concept for inland waterway vessels

Inland waterway transport plays a key role in regional freight logistics, particularly in Europe, where an extensive network of rivers and canals enables energy-efficient transportation of bulk goods, containers, and passengers. Compared to sea-going vessels, inland waterway vessels operate at significantly lower speeds and experience reduced resistance from wind and waves. As a result, their propulsion power demand is considerably lower, making them well suited for alternative propulsion concepts and early deployment of low-carbon fuels Typical European inland vessels of class IV, with a length of approximately 85 m and a width of 9.5 m, are commonly equipped with propulsion systems in the range of 600 kW. The highest power demand occurs during upstream operation against river currents, while long periods of low-load operation are characteristic for downstream travel and lock maneuvers. During lock passages, propulsion

power demand is minimal for extended durations, or the main engine is shut down entirely. These operating characteristics provide favorable conditions for hybrid propulsion architectures, in which battery systems can either supply propulsion power directly or be charged during low-load phases. Against this background, the CAMPFIRE project develops an ammonia-based propulsion system specifically tailored to inland waterway vessels [7]. The concept combines an ammonia-fueled combustion engine with an upstream cracking unit, an electrical generator, a battery system, and an electric propulsion motor coupled to the propeller shaft, see Figure 1. The combustion engine is supplied with liquid ammonia as the main fuel, while a small fraction of the ammonia is decomposed in the cracker to produce hydrogen for ignition stabilization. This configuration enables efficient ammonia utilization while decoupling engine operation from rapid load transients through electrical buffering.

Figure 1: Scheme of propulsion system of an inland waterway vessel consisting of NH_3 tank, NH_3 cracker, combustion engine, generator and battery.

Operational data recorded from an existing ammonia carrier called “Odin” operating on the River Rhine serve as the basis for system dimensioning and component layout, see

Figure 2. The measured load profiles are used both for the design of the hybrid powertrain and for defining representative operating points for engine and cracker testing under laboratory conditions. The hybrid architecture allows flexible operation strategies, including battery-only propulsion during lock passages and optimized steady-state operation of the combustion engine and cracker system, which reduces dynamic requirements and supports long-term durability.

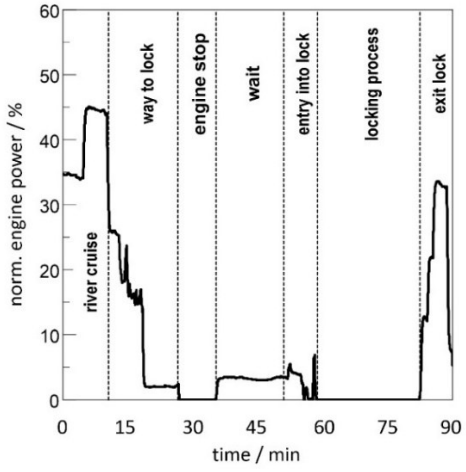

Figure 2: Engine power demand while locking process of MS Odin

The comparatively low propulsion power demand of inland vessels further facilitates the integration of ammonia as an energy carrier. However, shallow water operation represents an additional design constraint. Reduced water depths increase hydrodynamic resistance and significantly lower vessel speed at constant power, emphasizing the importance of propulsion system optimization and hull design for future inland vessels. The use of ammonia as a fuel introduces additional requirements with respect to ship layout and safety. Due to its classification as a hazardous substance, dedicated safety concepts are required, including double-walled fuel pipes, leak detection systems, gas-tight separation of machinery spaces, and active ventilation. These measures are integral parts of the overall system design and must be considered in parallel with propulsion system development.

Overall, the presented system concept demonstrates how the specific operational characteristics of inland waterway vessels can be leveraged to enable ammonia-based propulsion through a combination of hybridization, fuel processing, and robust safety design. The approach represents a technically realistic pathway for the decarbonization of inland shipping and serves as a scalable reference for future vessel concepts.

3. Development Methodology

3.1. Ammonia combustion

The development of suitable combustion concepts for ammonia fuelled engines requires a careful consideration of the specific fuel properties of ammonia in comparison to other energy carriers currently discussed for maritime and stationary applications. As summarized in Table 1, ammonia differs significantly from conventional gaseous and liquid fuels such as hydrogen, methane, and Diesel fuel.

Table 1 Fuel Properties [8, 9]

Description	**NH_3**	**H_2**	**Diesel**	**CH_4 (LNG)**
Lower heating value (MJ/kg)	18,6	12	42,7	46,4
Adiabatic flame temperature (°C)	1800	2110	2030	2000
Ignition temperature (°C)	630	560	> 225	470
Evaporation energy (kJ/kg)	1368	223	200-300	511
Tank size compared to Diesel fuel	2,8	4,2	1	1,3

In particular, its high auto-ignition temperature, limited flammability range in air, and comparatively low laminar flame speed indicate fundamentally different ignition and combustion behaviour. These characteristics clearly demonstrate that ammonia combustion cannot be realized efficiently without dedicated measures to support ignition and flame propagation. Consequently, the development methodology pursued in this work focuses on combustion

concepts that actively enhance both ignition reliability and combustion rate while maintaining a high energetic ammonia share. One widely discussed approach to address these challenges is pilot-assisted ammonia combustion using Diesel fuel. However, as the CAMPFIRE framework explicitly targets CO_2-neutral propulsion concepts, hydrogen was selected as ignition promoter instead. The combination of ammonia as a low-reactivity main fuel with hydrogen as a highly reactive additive represents a promising but nontrivial approach, as it introduces both synergistic effects and potential trade-offs that must be assessed experimentally.**Fehler! Verweisquelle konnte nicht gefunden werden.**Figure 3 provides an overview of the investigated injection configurations. In spark-ignited concepts, ammonia and hydrogen can either be supplied via port fuel injection or direct injection.

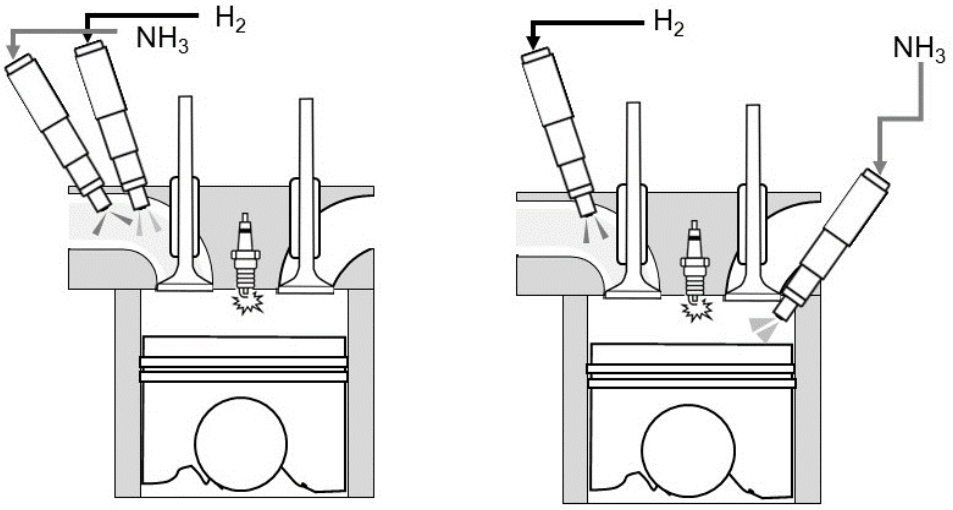

Figure 3: Overview of spark ignited (SI) combustion concepts with Ammonia and Hydrogen (promoter fuel). Left: Hydrogen and ammonia port fuel injection. Right: Hydrogen port fuel injection and ammonia direct injection [10].

A key focus of this study is the systematic comparison between dual port fuel injection of ammonia and hydrogen and high-pressure direct injection of ammonia at injection pressures up to 300 bar. While port fuel injection represents a comparatively simple and robust approach, high-pressure direct injection of ammonia offers several potential advantages. Direct injection of ammonia does not displace charge air in the intake manifold. This allows the boost pressure to be reduced. In addition, the combustion chamber is cooled, which reduces the tendency to knock.

Initial investigations were conducted on a single-cylinder research engine operated at a constant engine speed of 1500 rpm and an air-fuel-ratio of 1. Comparable load points were defined across all concepts to ensure meaningful evaluation. The assessment criteria include combustion stability expressed by the coefficient of variation of indicated mean effective pressure, fuel consumption, exhaust gas emissions with a focus on NO_x, N_2O, H_2 and unburned ammonia. A central objective of the methodology is to achieve stable and efficient combustion.

3.2. Testbed and single cylinder engine

The experimental investigations were conducted on a fully instrumented single-cylinder research engine derived from a Liebherr D966 Diesel engine. A schematic overview of the experimental test bench is shown in Figure *4*.

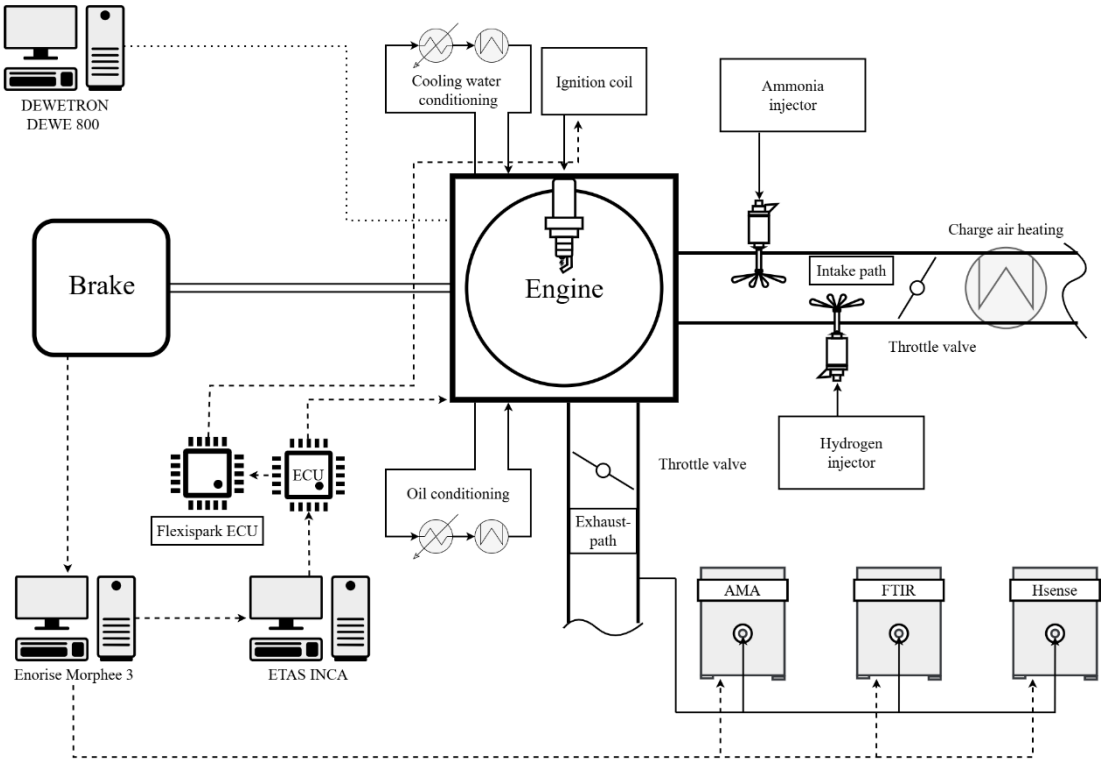

Figure 4: Scheme of the Single Cylinder Engine Testbench.

To enable spark-ignited operation, the cylinder head was modified such that the original Diesel injector position was replaced by a sleeve accommodating a centrally located spark plug. This configuration ensures a representative ignition location while preserving the geometric characteristics of the original combustion chamber. The ammonia high pressure direct injector is located on the side of the combustion chamber. The intake system can accommodate one injector for hydrogen and one injector for ammonia, enabling flexible adjustment of injection strategy and fuel ratios. The engine was coupled to a dynamometer, allowing precise control of engine speed and load throughout the experimental campaign. In-cylinder pressure was measured using a piezoelectric pressure transducer connected to a piezo charge amplifier and referenced to crank angle by an optical encoder with a resolution of 0.1 crank-angle degrees. This setup enables high-resolution cycle-resolved combustion analysis. Intake pressure, exhaust pressure, and ammonia fuel pressure were measured using absolute piezo-resistive pressure sensors.

All measurement signals were recorded using a high-speed data acquisition system, allowing real-time monitoring and evaluation of the combustion process (DEWETRON DEWE 800). Key combustion parameters, including heat-release rate and cycle-to-cycle variability, were derived from in-cylinder pressure measurements. For each operating point, heat-release analysis was performed over 100 consecutive engine cycles to ensure statistically robust results.

Fuel mass flow rates were measured using a Coriolis mass flow meter (Endres & Hauser

GmbH+Co. KG), while the intake air mass flow was determined using a rotary piston flow meter. The exhaust oxygen concentration was measured using a wide-band lambda sensor (Robert Bosch GmbH, LSU 4.9) connected to a lambda control unit (ETAS GmbH), enabling accurate determination of the air-fuel ratio. Exhaust gas concentrations of CO_2, O_2, and NO_x were measured using a standard exhaust gas analyzer (AVL AMA 4000). In addition, NH_3, N_2O, and NO_x were quantified using a Fourier-transform infrared (FTIR) spectrometer (IAG Gas Analytics GmbH), while H_2 concentration in the exhaust was measured using a mass spectrometer based on electron impact ionization HSense (MS4 Analysetechnik GmbH).

To assess knock tendency, a pressure-based knock criterion was applied following the Mannesmann method. The in-cylinder pressure signal was high-pass filtered separately in defined crank angle windows before and after top dead center (TDC) to isolate high-frequency pressure oscillations associated with knock. The resulting filtered signals were then evaluated by forming the ratio of the post-TDC to the pre-TDC signal intensity. A ratio close to unity indicates normal combustion without knock, as the high-frequency content remains at background level. An increasing ratio, however, reflects amplified pressure oscillations after TDC and is therefore interpreted as the onset and intensification of knocking combustion.

The main geometric and operational parameters of the single-cylinder engine are summarized in Table *1*.

Table 1: Single Cylinder Engine Data

Engine	**Detail**
Stroke (mm)	157
Bore (mm)	135
Max. Speed (rpm)	1900
Operation principle	4-stroke SI
Displacement	2,24
Compression Ratio	18,5
Type	Modified Liebherr Diesel-fuel engine based on D966

3.3. High-Pressure Ammonia Direct Injection Concept

For the investigations of high-pressure ammonia direct injection, a dedicated fuel supply system was implemented, see Figure *5*. Liquid ammonia was provided from pressurized bottles at an initial pressure of approximately 8 bar. In a first compression stage, the ammonia was compressed pneumatically to 20 bar in order to fill a piston accumulator. After completion of the filling process, the piston accumulator was further pressurized using nitrogen, increasing the ammonia pressure up to 300 bar. This two-stage pressurization concept allowed stable and reproducible high-pressure operation while maintaining a clear separation between the filling process and the final high-pressure generation.

A check valve was installed downstream of the filling line to prevent any backflow of the highly pressurized ammonia into the refueling and low-pressure supply system, ensuring safe operation

and pressure stability of the system. Following compression in the piston accumulator, the ammonia mass flow rate and pressure were measured using a Coriolis mass flow meter combined with pressure sensors. The pressurized ammonia was then injected directly into the combustion chamber using a commercially available gasoline direct injection (GDI) injector.

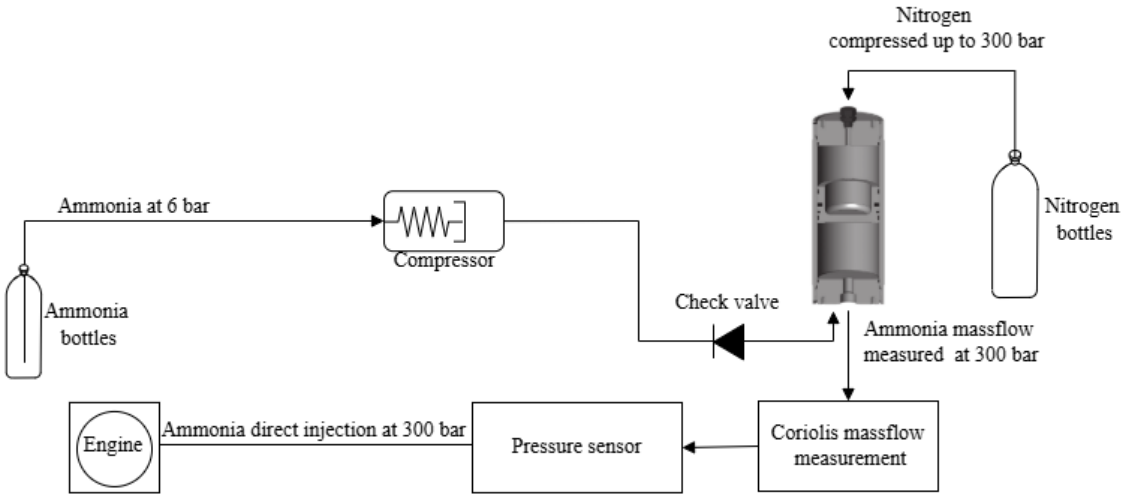

Figure 5: Ammonia high pressure direct injection infrastructure setup

A high-pressure direct injector from the passenger car sector (Bosch HDEV6) was employed for ammonia direct injection. The HDEV6 is a solenoid-actuated, multi-hole injector originally developed for gasoline direct injection systems and capable of operating at elevated injection pressures typical for modern spark-ignition engines. The injector features a multi-orifice nozzle layout that promotes efficient atomization and mixture formation. The resulting spray consists of multiple discrete plumes forming a hollow-cone-like spray structure, which supports rapid fuel-air mixing [11]. In the present configuration, the injector was installed with the spray axis inclined relative to the injector body axis, resulting in a spray deflection of approximately 45°. This orientation was required because the injector was positioned laterally in the cylinder head rather than centrally. The spray was therefore directed towards the piston bowl center to enhance in-cylinder mixture preparation and to promote interaction of the fuel jets with piston-induced flow structures.

Due to the multi-hole configuration, the injector generates several individual fuel jets with comparatively small droplet diameters, which enhances evaporation and mixture homogeneity. For the experiments conducted in this study, a single injection strategy was applied. The start of injection (SOI) for both port fuel injection (PFI) and direct injection (DI) was set to 265 °CA bTDC, corresponding to an intake-synchronous injection timing. It should be noted that the injector used was not specifically designed or optimized for ammonia operation. As a consequence, limited injector durability and comparatively short operating lifetimes were observed, which were taken into account during the experimental campaign.

For port fuel injection, a Liebherr multifuel injector was used. The injector is solenoid-actuated and designed for gaseous and liquid alternative fuels. In contrast to the direct injector, the PFI injector features a single-orifice nozzle configuration and was operated at an injection pressure of 20 bar. The spray formation of the injector is achieved by means of a blow cap, which shapes and disperses the fuel jet after leaving the nozzle. This design promotes enhanced atomization and spray dispersion at comparatively low injection pressures, supporting fuel-air mixing within the intake port.

3.4. High Energy Ignition System

Due to the unfavourable ignition properties of ammonia, including its high auto-ignition temperature and low laminar flame speed, a high-energy ignition (HEI) system Flexispark provided SEM AB was applied in this study to ensure stable and reproducible combustion. The HEI concept provides increased ignition energy through extended spark duration and higher discharge power, thereby promoting reliable flame kernel formation, particularly for lean and highly diluted ammonia-containing mixtures [12]. Detailed investigations of HEI for ammonia–hydrogen combustion have previously been published in the CIMAC literature (2025), where stable engine operation in every load point with up to 100 % energetic ammonia share using a double-PFI concept was demonstrated [6, 13]. In this paper, the HEI system is used in 100% ammonia operation in ammonia PFI configuration.

4. Results Combustion Process Development

This section presents a systematic investigation of the combustion behaviour of a liquid high-pressure ammonia direct injection (NH_3-DI) concept and compares it to established liquid ammonia port fuel injection (PFI) combustion strategies. The results are structured to first establish a lambda variation followed by an energetic ammonia share variation and the last results are about an ignition timing variation. Further optimization potential will then be identified.

4.1. Lambda variation

To evaluate the potential of high-pressure ammonia direct injection (NH_3-DI), a comparative lambda study was conducted against the established ammonia spark-ignited port fuel injection concept with hydrogen support (NH_3-PFI-H_2). The objective of this comparison is to identify fundamental differences in combustion stability, efficiency, combustion phasing, and emission formation mechanisms under comparable operating conditions. For all spark-ignited operating points, the default ignition timing strategy of the HEI system was applied, ensuring consistent and comparable ignition conditions across both combustion concepts.

The lambda variation was performed at a constant indicated mean effective pressure of 17 bar IMEP while varying the excess air ratio (λ). Hydrogen was used as combustion support for both spark-ignited concepts. The NH_3-DI concept was operated with a rail pressure of 300 bar, and the ammonia PFI rail pressure was set to 20 bar. The start of ammonia injection was 265 °CA bTDC for both concepts and the energetic ammonia share was kept constant to 85 %.

Figure *6* shows the CoV_{IMEP} for the investigated combustion concepts. The NH_3-DI concept exhibits significantly lower cycle-to-cycle variations across the entire air-fuel-ratio range. Stable operation with CoV_{IMEP} values well below 3 % is achieved from near-stoichiometric to lean conditions of lambda 1.4. In contrast, the NH_3-PFI-H_2 concept shows a pronounced increase in combustion variability with increasing lambda, approaching instability limits at lambda 1.2. The improved combustion stability of the DI concept can be attributed to enhanced in-cylinder charge cooling and stratified mixture formation resulting from high-pressure DI injection. These effects promote reliable ignition and stable flame propagation, particularly at lean operating conditions and elevated ammonia fractions. In addition, the direct injection strategy promotes a preferential transport of the port-injected hydrogen toward the spark plug region, creating a locally highly reactive ignition zone. Simultaneously, the directly injected ammonia penetrates deeper into the combustion chamber and is subsequently ignited by the hydrogen-stabilized flame kernel. This

targeted stratification enhances ignition robustness and flame stabilization compared to the PFI concept, where a homogeneous hydrogen–ammonia mixture is transported to the spark plug, resulting in lower local reactivity and increased sensitivity to combustion instabilities.

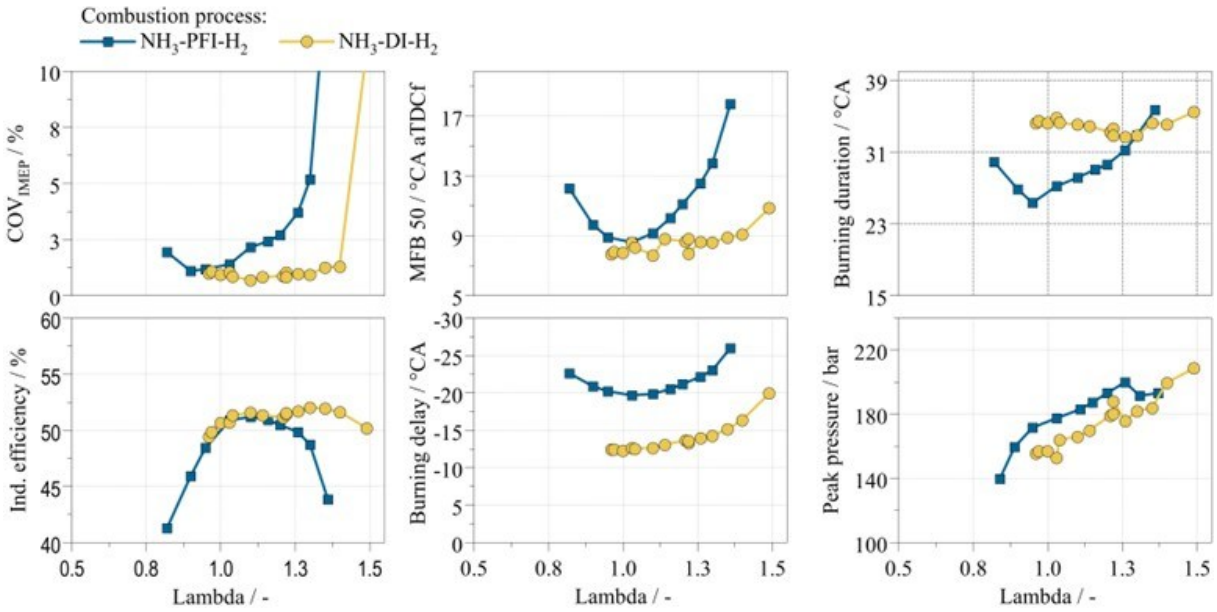

Figure 6: CoV_{IMEP}, MFB 50, burning duration, indicated efficiency, burning delay and peak pressure over the air-fuel-ratio (lambda) for the ammonia in PFI and DI combustion process

The combustion duration, defined as the crank angle interval between 10 % and 90 % mass fraction burned (MFB10–MFB90), is also shown in Figure *6*. In contrast to the ignition delay behaviour, the NH_3-PFI-H_2 concept exhibits slightly shorter combustion durations over a wide lambda range compared to the NH_3-DI concept. This can likely be attributed to the more homogeneous distribution of hydrogen within the premixed charge, which promotes faster global flame propagation once ignition has occurred. The NH_3-DI concept, however, shows a significantly shorter ignition delay, indicating the presence of locally hydrogen-enriched regions near the spark plug that facilitate rapid flame kernel formation and early combustion development. At later stages of combustion, the stratified charge structure of the DI process results in the gradual consumption of ammonia-rich zones distributed deeper within the combustion chamber. This leads to a slightly prolonged overall combustion duration compared to the premixed PFI concept.

Both combustion concepts show maximum indicated efficiencies close to stoichiometric conditions. However, the NH_3-DI concept maintains high efficiency levels over a wider lambda range. The NH_3-PFI-H_2 concept shows a noticeable efficiency drop toward lean operation. The improved efficiency of NH_3-DI is mainly attributed to the improved combustion stability and more favourable heat release phasing. The peak pressure increases for both combustion processes, with the peak pressure of the DI concept being slightly lower than that of the PFI concept due to the evaporation of ammonia in the combustion chamber.

Figure 7 shows the emission behaviour of both combustion concepts as a function of air-fuel-ratio. Ammonia slip is increasing for both concepts with leaner mixtures. This behaviour indicates

that complete ammonia conversion remains challenging for both combustion strategies and is primarily governed by reduced reaction rates at lean operating conditions.

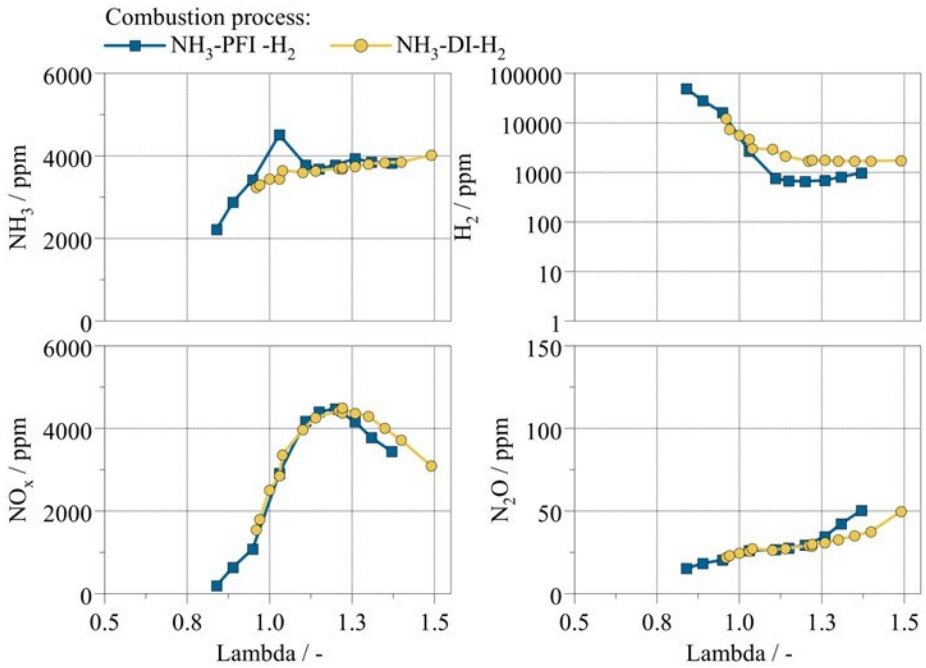

Figure 7: NH_3, H_2, NO_x and N_2O emissions over air-fuel-ratio (lambda) for spark ignited ammonia PFI and DI combustion process

Hydrogen emissions decrease with increasing lambda for both combustion concepts. This trade-off between low hydrogen emissions and high NO_x emissions can be observed in a similar way in both combustion processes. Higher combustion chamber temperatures due to a richer lambda mixture cause ammonia to be decomposed into hydrogen and nitrogen, resulting in less NO_x being produced. With excess air, this behaviour is reversed and less hydrogen is produced, but the excess oxygen leads to increased NO_x emissions. The NH_3-DI concept consistently exhibits slightly lower N_2O emissions compared to NH_3-PFI-H_2. This reduction suggests improved conversion of nitrogen-containing intermediate species due to enhanced local temperature and mixing conditions.

Overall, the results show that the NH_3-DI combustion concept significantly improves combustion stability and reduces ignition delay compared to premixed ammonia combustion with port fuel injection. While premixed hydrogen support increases the global flame speed and thus the combustion speed, the DI strategy improves ignition robustness and early flame stabilization but may prolong the late combustion phase due to mixture stratification. These improvements of the ammonia direct injection result in a slightly higher indicated efficiency and reduced N_2O formation with consistent ammonia slip.

4.2. Energetic ammonia share variation

Following the lambda variation, the influence of the energetic ammonia share on combustion behaviour is investigated. Increasing the ammonia fraction represents a key challenge for ammonia-fueled engines due to the low reactivity and slow kinetics of ammonia, which directly affect ignition stability, combustion duration, and emission formation. Spark-ignited (SI) experiments were conducted at air-fuel-ratio 1. The objective of this parameter study is to assess

how increasing energetic ammonia share impacts combustion stability, ignition behaviour, efficiency, and emissions for the NH_3-DI concept in comparison to NH_3-PFI-H_2 combustion. Particular emphasis is placed on identifying the operational limits and the mechanisms that enable an extended stable operating range for the direct injection concept.

Figure 8 presents the CoV_{IMEP} as a function of energetic ammonia share. For all combustion concepts, increasing the ammonia fraction leads to a deterioration of combustion stability due to reduced mixture reactivity. The NH_3-DI concept exhibits the lowest CoV_{IMEP} values over a wide range of energetic ammonia shares.

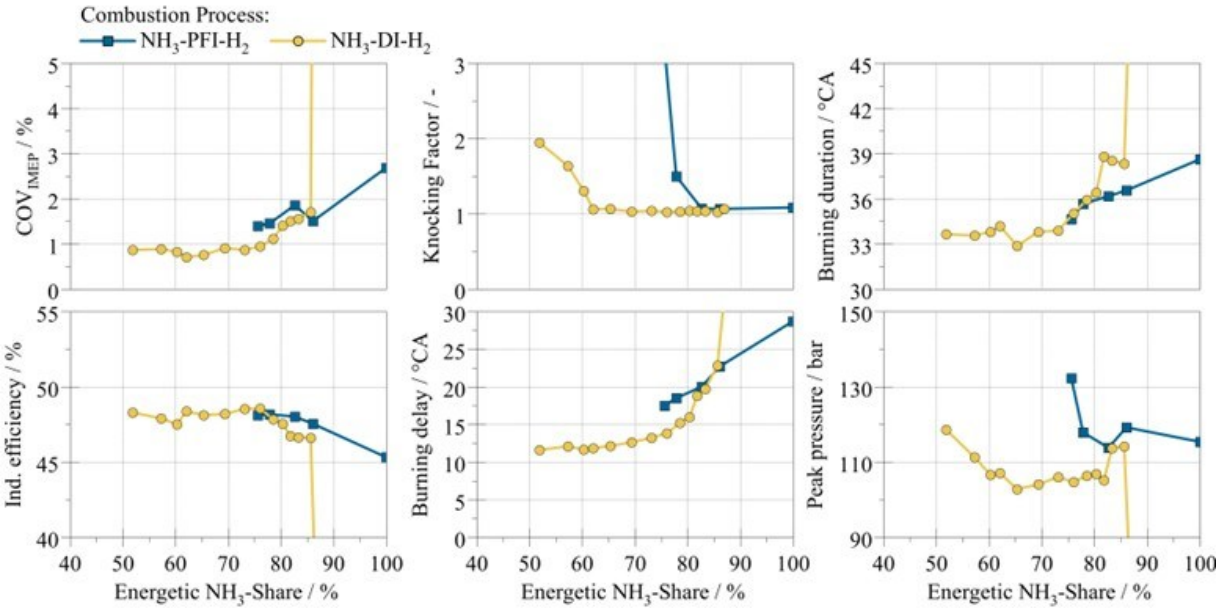

Figure 8: CoV_{IMEP}, knocking factor, burning duration, indicated efficiency, burning delay and peak pressure over the energetic NH_3-share for the ammonia PFI and DI combustion process

This improvement in combustion stability is attributed to the additional turbulence and enhanced local mixture preparation induced by the high-pressure ammonia direct injection. The increased charge movement improves the local ignition conditions at the spark plug and promotes more reproducible flame kernel formation, thereby reducing the burning delay of the ammonia direct injection. Furthermore, the injection strategy supports a preferential enrichment of hydrogen in the vicinity of the spark plug due to in-cylinder flow structures and mixture stratification effects. This locally hydrogen-enriched ignition zone increases the effective mixture reactivity at the ignition site and reduces sensitivity to cycle-to-cycle variations. The ammonia jet, in contrast, penetrates deeper into the combustion chamber and is subsequently consumed by the hydrogen-stabilized flame front. The combined effect of locally improved ignition conditions and controlled stratified combustion significantly contributes to the consistently low CoV_{IMEP} values observed for the NH_3-DI concept.

Despite these advantages, the maximum achievable energetic ammonia share was higher for the premixed PFI operation under the investigated conditions. This behaviour is linked to the thermodynamic differences between both injection concepts and the high energy ignition system. The spark duration was maintained longer at the PFI 100% ammonia measuring point. The NH_3-DI-H_2 operation results in lower peak cylinder pressures and consequently lower combustion temperatures compared to premixed operation. While the additional cooling effect of directly injected ammonia supports knock mitigation, it simultaneously reduces mixture reactivity at very

high ammonia shares, which can negatively influence ignition capability and limits the operable substitution range. The significantly increases the achievable energetic hydrogen share under engine-relevant conditions. The NH_3-DI-H_2 allows at a high compression ratio stable operation with up to 45 % hydrogen without the occurrence of knocking, which exceeds the limits reported for other combustion concepts. This improvement is attributed to the strong cooling effect of ammonia evaporation in direct injection.

Further insight into the combustion characteristics is provided in Figure 8 by the comparison of in-cylinder pressure, total heat release and mass fraction burned (MFB) curves at an energetic ammonia share of 85 % and identical spark timing of 26 °CA bTDC. The ignition delay under these conditions is nearly identical for both combustion concepts, with the NH_3-PFI-H_2 concept initiating combustion approximately 1 °CA earlier than the NH_3-DI-H_2 concept. The NH_3-DI-H_2 concept exhibits a noticeably lower peak cylinder pressure compared to the NH_3-PFI-H_2 concept. This behaviour indicates a less concentrated and more distributed heat release, which is consistent with the stratified mixture formation of the direct injection process.

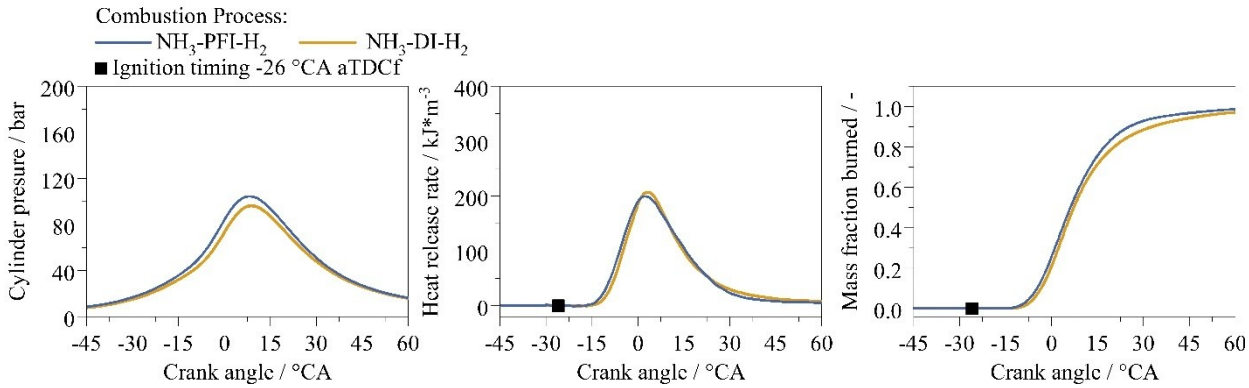

Figure 9: Cylinder pressure, heat release and mass fraction burned over crank angle for the ammonia DI and PFI combustion process at 85 % energetic NH_3 share.

The MFB curves further confirm these differences in combustion progression. While the NH_3-PFI-H_2 concept shows a faster overall combustion development after ignition, the NH_3-DI-H_2 concept demonstrates a more gradual burn-out phase with combustion extending further into the expansion stroke. This prolonged late combustion phase is attributed to the stratified charge structure created by ammonia direct injection. Hydrogen, which is preferentially transported toward the spark plug region, supports rapid flame kernel formation and early combustion development. However, ammonia-rich zones penetrating deeper into the combustion chamber are consumed later by the propagating flame front, resulting in a delayed completion of combustion.

Regarding the emissions in Figure 10, both ammonia slip and unburned hydrogen emissions decrease with increasing energetic ammonia shares for all investigated combustion concepts. This behaviour is primarily related to the reduced hydrogen support fraction and improved overall ammonia conversion at higher energetic ammonia shares. NO_x emissions do not show a distinct systematic trend and appear to be mainly influenced by small variations in the global air-fuel-ratio. The N_2O emissions are increasing slightly with increasing energetic ammonia share within a range of approximately 30 to 40 ppm because they are not completely oxidized due to the longer burning duration.

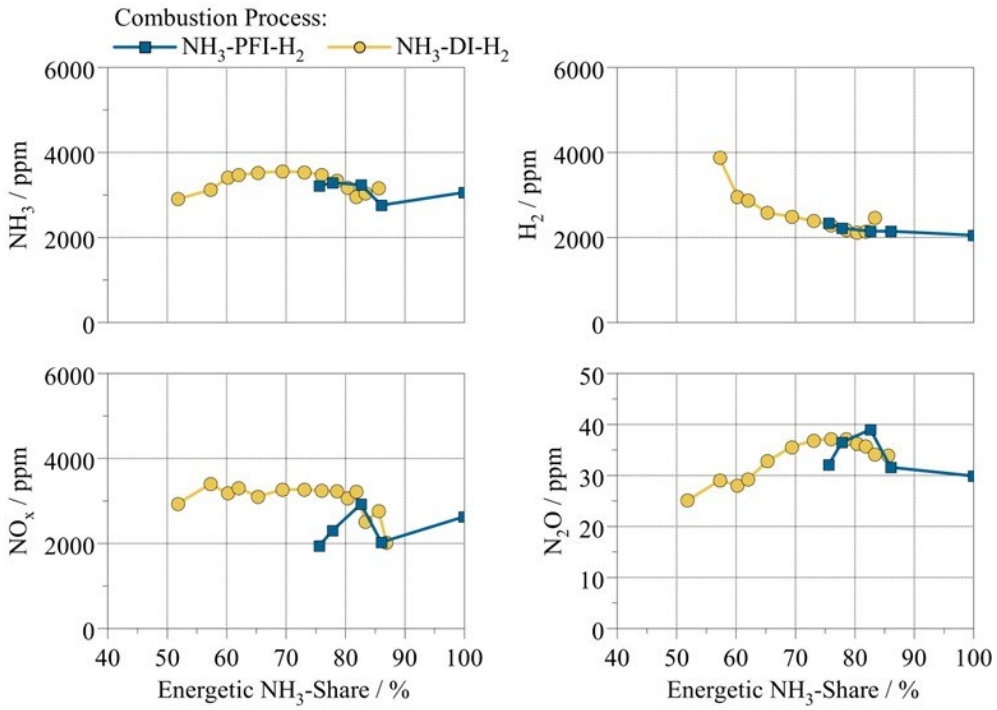

Figure 10: NH_3, H_2, NO_x and N_2O emissions over the energetic NH_3-share for the ammonia DI and PFI combustion concepts

4.3. Ignition timing variation

Following the analysis of the achievable energetic ammonia share, the influence of ignition timing on combustion stability and efficiency was investigated. The comparison was performed at an indicated mean effective pressure of 17 bar IMEP and 75 % energetic ammonia share for ammonia direct injection and port fuel injection.

Figure 11 shows that CoV_{IMEP} again indicates a clear stability advantage of the DI combustion concept. Across the entire investigated ignition timing range CoV_{IMEP} remained below 3 % for DI operation, demonstrating highly stable combustion. Furthermore, the combustion phasing in ammonia DI configuration remained stable within an ignition timing window of 17 °CA aTDC to 8 °CA bTDC. At earlier ignition timings, combustion tends to knock, which is also reflected by the increasing knocking factor shown in Figure 11. In contrast, PFI operation already showed an increasing knocking tendency at ignition timings earlier than 16 °CA bTDC and unstable operation at 15 °CA bTDC. The ignition delay was also shorter for the DI concept, indicating improved local mixture reactivity at the spark plug. The DI concept additionally achieved a more stable indicated efficiency compared to PFI operation, suggesting reduced sensitivity to suboptimal ignition timing.

A possible explanation for this behaviour is related to the different mixture preparation mechanisms of both concepts. In the DI configuration, hydrogen and air are introduced via port fuel injection, while ammonia is injected directly into the combustion chamber. This promotes the formation of a locally hydrogen-enriched and highly reactive mixture near the spark plug, whereas the ammonia penetrates deeper into the cylinder volume. Such localized stratification improves ignition robustness and reduces cycle-to-cycle variability, resulting in lower CoV_{IMEP} values.

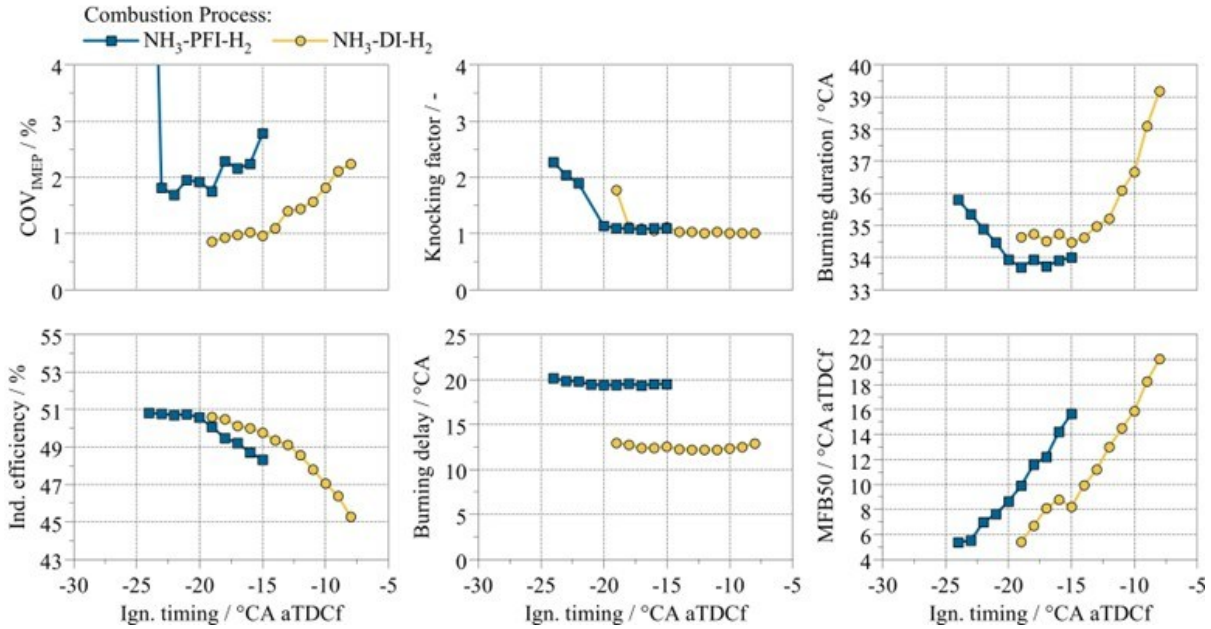

Figure 11: CoV_{IMEP}, knocking factor, burning duration, indicated efficiency, burning delay and MFB50 over the ignition timing for the ammonia-PFI and DI combustion process.

In contrast, the PFI concept transports a largely homogeneous hydrogen–ammonia–air mixture toward the spark plug. Although this promotes uniform global combustion once ignition is established, the locally reduced hydrogen concentration at the ignition site can lower mixture reactivity and increase sensitivity to ignition timing variations. After ignition, the initially fast hydrogen-supported flame in DI operation encounters ammonia-rich regions that contain less locally available hydrogen, which can prolong the late combustion phase due to the low laminar flame speed of ammonia. This behaviour explains the observed longer combustion duration for the DI concept. This behaviour is supported by the findings of Lin *et al.* (2024), who compared ammonia port fuel injection (PFI) with ammonia direct injection (DI) in a hydrogen-supported SI engine [14]. They observed that the ammonia DI results in a more inhomogeneous fuel distribution with hydrogen consumed earlier than ammonia, which leads to more rapid early-stage combustion relative to the PFI case. This supports the hypothesis that direct injection enhances local reactivity near the spark plug by preferentially delivering hydrogen-rich mixtures to the ignition site, while ammonia-rich regions are consumed later in the combustion process. This hypothesis is further supported by the comparison of cylinder pressure, heat release rate, and mass fraction burned (MFB) traces for NH_3-DI-H_2 and NH_3-PFI-H_2 at identical ignition timing of 18 °CA bTDCf, shown in Figure 12.

The DI concept exhibits a higher cylinder pressure level and a reduced ignition delay compared to the PFI configuration, confirming improved local mixture reactivity at the spark location. The combustion phasing analysis shows that the DI concept reaches an MFB50 of 7.5 °CA aTDC, whereas the PFI concept reaches MFB50 at approximately 10 °CA aTDC. The earlier combustion phasing of the DI process explains the higher peak cylinder pressure and indicates a more efficient early heat release.

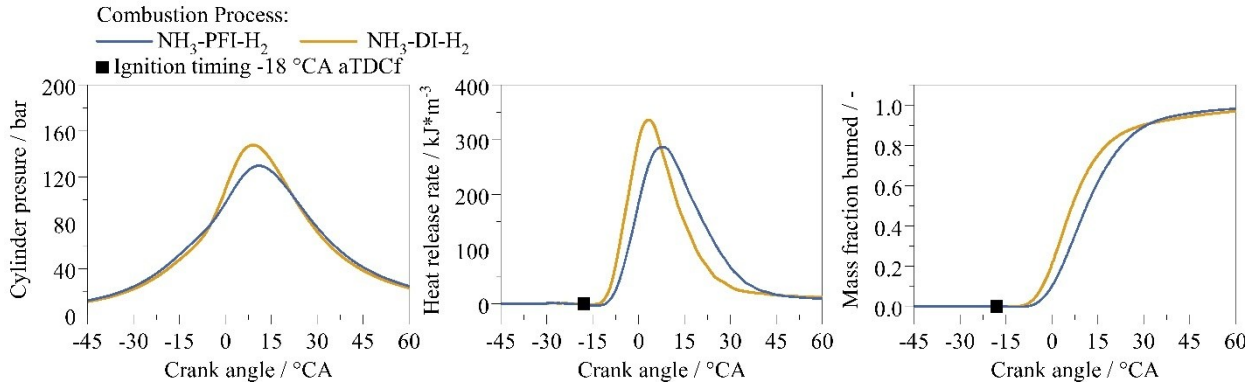

Figure 12: Cylinder pressure, heat release and mass fraction burned over crank angle for the ammonia DI and PFI combustion process at 75 % energetic NH_3 share.

The MFB and heat release rate curves further reveal distinct differences in combustion progression. The DI concept shows a steeper initial heat release, indicating faster flame kernel development and early combustion acceleration. However, the slope of the MFB curve decreases during later combustion stages, resulting in a slightly delayed burn-out phase compared to the PFI concept. This behaviour is consistent with the stratified mixture formation of the DI process, where hydrogen-enriched zones near the spark plug promote rapid combustion initiation, while ammonia-rich regions located deeper in the combustion chamber burn more gradually.

Figure 13 shows ammonia slip increased slightly with later ignition timing for all both combustion concepts.

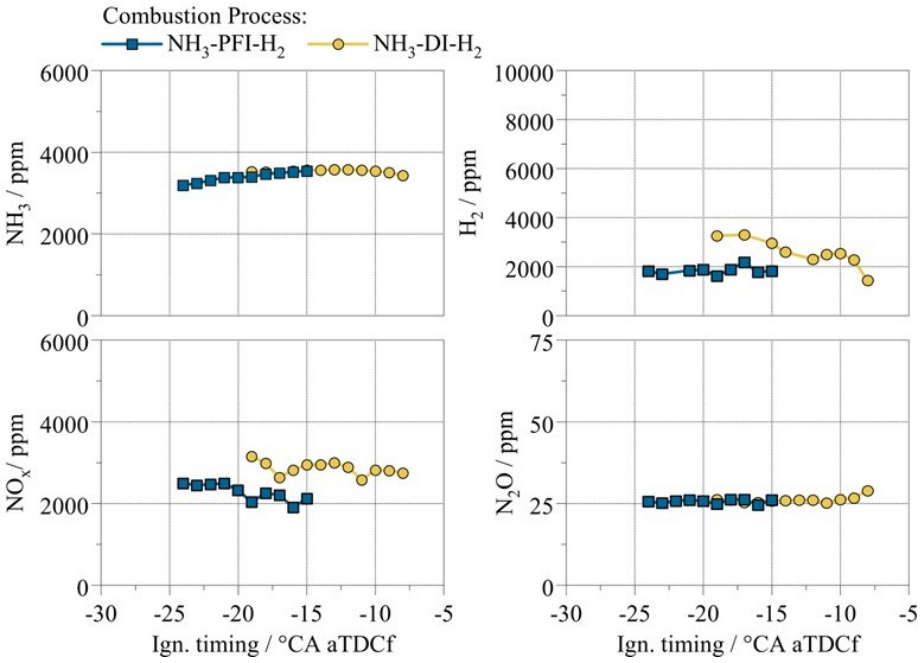

Figure 13: NH_3, H_2, NO_x and N_2O emissions over the ignition timing for the ammonia PFI and DI combustion process.

This trend is attributed to delayed and slower combustion, which reduces the available time and temperature level for complete ammonia oxidation. The effect is consistent with the observed increase in combustion duration and the shift of heat release further into the expansion stroke at late ignition timings. The DI concept exhibited slightly higher hydrogen emission levels, while PFI

operation resulted in the lower values. Notably, hydrogen emissions for the DI concept decreased with later ignition timing. This trend suggests improved oxidation of intermediate species due to enhanced mixing and a more distributed heat release, which is consistent with the longer combustion duration and reduced premixed fraction at later injection timings.

NO_x emissions decreased for both combustion concepts with retarded ignition timing or injection timing. This trend directly correlates with the reduction in peak combustion temperatures and the delayed heat release, as previously indicated by the exhaust gas temperature measurements and combustion phasing analysis. The reduced residence time at high temperature levels limits thermal NO formation, making ignition timing an effective control parameter for NO_x emissions in ammonia-fueled combustion. N_2O emissions remained nearly constant for both spark-ignited combustion concepts (PFI and DI) over the investigated ignition timing range. This indicates that N_2O formation in these concepts is relatively insensitive to ignition timing under the investigated conditions and is likely dominated by chemical pathways rather than peak temperature effects.

4.4. Optimisation potential

Further optimization potential of the direct injection (DI) strategy can be expected from an advanced control of mixture formation and heat release shaping. In particular, split or multiple injection strategies offer the possibility to tailor ignition conditions and local equivalence ratios more precisely. A small pre-injection could be used to promote stable ignition and reduce ignition delay, while a subsequent main injection enables higher energetic ammonia shares. Additionally, post-injections may support the oxidation of unburned NH_3 and H_2, thereby mitigating slip and improving overall combustion efficiency.

In addition to the previously discussed measures, further optimization potential of the DI concept arises from the inherently low knock tendency of ammonia-containing mixtures. Due to the high auto-ignition temperature and low laminar flame speed of NH_3, the susceptibility to knock is significantly. This opens the possibility to increase the geometric compression ratio without encountering knock limitations. An elevated compression ratio would directly improve the thermodynamic efficiency according to the ideal cycle considerations and could therefore provide a further increase in brake thermal efficiency, particularly at higher ammonia substitution rates. Moreover, the exhaust gas characteristics of ammonia combustion offer opportunities for simplified aftertreatment integration. The presence of residual ammonia slip in the exhaust ant the preferred air-fuel-ratio of 1 can be utilized in a three-way catalytic converter system to reduce NO_x, N_2O, H_2 and NH_3 emissions without the need for additional urea dosing.

Finally, further experimental investigations with a high-energy ignition system represent an additional optimization pathway towards higher energetic ammonia shares in DI configuration. For ammonia PFI configuration it could be shown that 100% ammonia combustion is feasible over the entire load range of the engine [6, 13]. A reduction of the hydrogen support fraction would simplify onboard fuel logistics and further strengthen the viability of ammonia as a primary carbon-free fuel.

5. Conclusion & Outlook

This study investigated spark-ignited ammonia combustion using port fuel injection (NH_3-PFI-H_2) and high-pressure ammonia direct injection (NH_3-DI-H_2) at 1500 rpm, focusing on combustion stability, ignition behaviour, efficiency, and emissions. The results clearly demonstrate that ammonia direct injection provides significant advantages in combustion robustness. Across all investigated operating conditions, the DI concept consistently achieved lower CoV_{IMEP} values and maintained stable combustion even at high energetic ammonia shares and lean mixtures. A key contributor to this behaviour is the stratified mixture formation generated by the direct injection process. The DI strategy promotes preferential transport of port-injected hydrogen toward the spark plug, creating a locally highly reactive ignition zone. Simultaneously, ammonia penetrates deeper into the combustion chamber and is subsequently consumed by the hydrogen-stabilized flame front. This targeted stratification improves ignition reliability and reduces sensitivity to mixture fluctuations [14].

Consistent with this mechanism, the DI concept showed a significantly shorter ignition delay compared to PFI operation, indicating enhanced local mixture reactivity at the spark location. Despite this faster combustion initiation, DI exhibited a slightly longer overall combustion duration. This behaviour is attributed to the gradual consumption of ammonia-rich zones located further away from the ignition source, which burn slower due to the inherently low laminar flame speed of ammonia. The combination of fast ignition and controlled late-stage combustion results in highly stable and smooth heat release characteristics. From a thermodynamic perspective, both combustion concepts achieved comparable indicated efficiencies and similar emission levels over the investigated operating range. However, the DI concept demonstrated clear operational advantages by maintaining stable efficiency under lean conditions and high ammonia shares. Furthermore, the strong charge cooling effect of ammonia direct injection enabled operation with substantially higher hydrogen fractions without knocking. This significantly increases tolerance toward mixture composition variations while simultaneously preventing knock-induced mechanical stress on engine components.

Overall, ammonia direct injection emerges as a highly promising combustion strategy. The concept combines superior combustion stability, reduced ignition delay, high knock resistance at elevated hydrogen fractions, and comparable efficiency and emission performance relative to premixed ammonia combustion. These characteristics highlight the strong potential of spark ignited DI-based ammonia combustion as a robust and scalable solution for future low-emission engine applications.

6. Achnowledgements

This work was carried out within the CAMPFIRE project of the Hydrogen Flagship Project TransHyDE and was funded by German Federal Ministry for Education and Research. The authors would like to thank Robert Bosch GmbH for providing technical support and the injection hardware used in this study.

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