CIMAC CONGRESS 25
ZURICH, MAY 19 – 23, 2025

2025 | 341

Ammonia-based powertrain with onboard feneration of hydrogen for small ICEs

Fuels - Alternative & New Fuels

Benjamin Stengel, FVTR GmbH

Florian Mach, FVTR GmbH
Thomas Sadlowski, FVTR GmbH
Fausto Tidona, ZBT GmbH
Jannick Plass, ZBT GmbH
Fabian Jochmann, ZBT GmbH

ABSTRACT

Reducing greenhouse gas emissions will continue to be the main development goal in sectors such as transportation, buildings and industry in the coming decades. Now that the emission of pollutants (SOx, NOx, soot) in maritime propulsion systems has been significantly reduced using sulfur-free fuels and exhaust gas aftertreatment components, the drastic reduction in CO2 emissions (IMO: net-zero CO2 by 2050) requires a switch to CO2-free fuels. The most promising options here are ammonia and hydrogen. Both are not drop-in fuels and, due to their toxicity (ammonia) and high ignitability (hydrogen), require significant changes in the fuel supply structure and adjustments to the engine and engine control system. In addition to CO2-free ship propulsion systems for ferries and container ships, small ships and boats are forced to reduce their greenhouse gas emissions. As part of a publicly funded research project, an ammonia-based CO2-free propulsion system for a sailing yacht is presented here.

The propulsion system is based on a converted LPG engine that runs on a mixture of hydrogen and ammonia. The ammonia is stored on board the yacht in pressurized gas cylinders and will be vaporized for further use. An ammonia cracker module converts ammonia on board the yacht into hydrogen and nitrogen using a fixed-bed reactor by catalytically cracking the ammonia through the addition of heat. The product gas from the cracker is blown into the intake path in the engine via PFI injectors. In addition, gaseous ammonia is added to the engine's intake air via a proportional valve and the fuel-air mixture is then ignited by a spark plug in the cylinder. The hydrogen-rich cracker product gas provides the ignition fuel for safe ignition of the ammonia-hydrogen mixture, and the ammonia content can be increased with increasing engine load. Safe engine operation up to 80% ammonia content has been demonstrated in test bench trials.

As part of this work, engine operation with pure hydrogen, hydrogen-ammonia mixture and cracker product gas-ammonia mixture in the power range of up to 15 kW engine power (typical sailing yacht propulsion) was investigated. While the focus in pure hydrogen operation was primarily on avoiding combustion anomalies (pre-ignition, knocking, backfire), the admixture of ammonia showed a prolonged combustion duration and a shift of the center of combustion due to the low laminar flame speed. It was shown that up to 30 % higher mean effective pressures were possible with NH3 admixture at the same knocking peak. In addition to the tests on the effect of the individual fuel mixtures on combustion, the ECU maps were also calibrated accordingly for operation on the sailing yacht with engine-cracker coupling. After the test bench tests, the drive system was implemented in a sailing yacht together with other modules for fuel supply and ammonia disposal.

1 INTRODUCTION

Ammonia (NH_3) as a fuel offers an innovative solution for achieving lower carbon emissions in the transportation and energy sectors, particularly through its integration in marine and off-grid applications where reducing CO_2 emissions is crucial. The "Campfire 07" project, funded by the German Federal Ministry of Education and Research, explores the practical application of ammonia as a fuel by developing an ammonia-based powertrain that generates hydrogen onboard for use in an ICE. This engine, originally designed for liquefied petroleum gas (LPG), has been modified to run on a dual-fuel mixture of ammonia and hydrogen, where hydrogen is produced by a thermal cracker from ammonia feedstock. The system was initially tested in laboratory settings before being installed on a sail yacht, where its performance was evaluated in real-world conditions.

Ammonia presents several advantages as a fuel alternative. First, it has no carbon content, which means that its combustion does not directly produce CO_2, offering a pathway to carbon-neutral propulsion systems when produced from renewable energy sources. Furthermore, ammonia serves as an efficient hydrogen carrier, providing an easier and more cost-effective method for transporting and storing hydrogen than compressed or liquefied hydrogen gas. The project's powertrain configuration includes the port fuel injection of hydrogen alongside controlled ammonia dosing to the intake air, thus achieving the desired air-fuel mixture and enabling reliable ignition with spark plugs.

Despite these advantages, using ammonia as a fuel poses several technical challenges, particularly due to its high ignition temperature, low flame speed, and narrow flammability limits, which make stable combustion difficult to achieve in traditional engine designs. However, by combining ammonia with hydrogen - a fuel with a high flame speed and wide flammability range - the Campfire 07 project aims to mitigate these limitations, enhancing ammonia's suitability for combustion engines. This approach is expected to yield an efficient, low-emission solution for marine propulsion systems, with applications extending to other sectors seeking carbon-neutral solutions.

The following sections detail the properties of ammonia and hydrogen as fuels for internal combustion engines, providing a scientific foundation for the project's NH_3/H_2 approach and discussing the benefits and limitations inherent to each fuel type.

2 PROPERTIES OF AMMONIA AND HYDROGEN AS FUELS FOR INTERNAL COMBUSTION ENGINES

Ammonia and hydrogen exhibit distinctive properties that significantly influence their suitability and behavior in internal combustion engines. Ammonia, a carbon-free substance, and hydrogen, the simplest and most energy-dense element, each present unique combustion characteristics that require careful consideration in the context of engine design, fuel injection strategies, and ignition systems.

2.1 Ammonia as a Fuel

Ammonia's potential as an alternative fuel lies primarily in its carbon-free composition, which can contribute to CO_2 emission reductions across various applications. Its chemical and physical properties make it an attractive hydrogen carrier, often referred to as a "hydrogen vector". Stored under moderate pressures (10 bar) or at low temperatures (-33.5°C) [8], ammonia remains in a liquid state, allowing for relatively straightforward handling and storage, similar to liquefied petroleum gas (LPG) systems commonly used in the industry.

From a thermodynamic perspective, ammonia's lower heating value (LHV) is 18.6 MJ/kg, which is about one-sixth of hydrogen's (120 MJ/kg), Figure 1. This lower energy density means that larger volumes of ammonia are required to produce equivalent energy outputs, necessitating higher fuel storage capacity on vehicles or vessels. In terms of combustion, ammonia has an auto-ignition temperature of approximately 650°C and a narrow flammability range of 0.63–1.4 equivalence ratios, making it challenging to ignite and sustain stable combustion within conventional engine configurations, Table 1.

The high ignition temperature and slow flame speed of ammonia (0.07 m/s) contribute to combustion instability, which complicates its application in single-fuel systems, Table 1. Consequently, spark ignition engines running on ammonia would require advanced ignition assistance, or in most cases, a dual-fuel approach to stabilize combustion and improve performance. The Campfire 07 project addresses these challenges by injecting hydrogen into the intake air, enhancing the overall flammability and stability of the ammonia-hydrogen mixture.

2.2 Hydrogen as a Fuel

Hydrogen stands out due to its exceptionally high LHV of 120 MJ/kg, making it one of the most energy-dense fuels by mass. Additionally, hydrogen's low molecular weight (2.016 g/mol) and

Table 1. Properties of ammonia and hydrogen in comparison to conventional fuels

Fuel	**NH_3**	**H_2**	**CH_4**	**C_3H_8**	**Gasoline**	**Diesel**
Lower heating value in MJ/kg	18.6[1]	120[1]	50.0[1]	46.4[1]	44.5[2]	42.5[2]
Heat of vaporization in kJ/kg	1371	460[5]	511[6]	426[5]	~355[5]	250[6]
Stoichiometric air-fuel ratio	6.1[3]	34.3[2]	17.2[2]	15.6[2]	14.6[2]	14.5[2]
Energy content / stoich. Mixture in MJ/kg	2.62	3.4	2.75	2.80	2.85	2.74
Density in kg/m³	603[4]	71[4]	417[1]	512[1]	700[4]	850[4]
Minimum autoignition temperature in °C	650[1]	520[1]	630[1]	450[1]	260 – 460[2]	180 – 320[2]
Flammability limit (equivalence ratio)	0.63 – 1.4[1]	0.1 - 7.7[7]	0.5 – 1.7[1]	0.49 – 2.5[7]	0.7 – 2.5[7]	0.75 – 2[7]
Flammability limit (mass fraction %)	9 – 18.9[1/3]	4 – 75[2]	5 – 15[2]	2.1 – 9.5[2]	1.3 – 7.1[2]	0.6 – 5.5[2]
Adiabatic flame temperature in °C	1800[1]	2110[1]	1950[1]	2000[1]	2307[2]	2327[2]
Maximum laminar flame speed in m/s	0.07[1]	2.91[1]	0.37[1]	0.47[7]	~0.4[7]	~0.4[7]

high diffusivity enable it to disperse rapidly, reducing the risk of localized high concentrations in air. Compared to ammonia, hydrogen's flame speed (2.91 m/s) and adiabatic flame temperature (2110°C) [1] are significantly higher, which supports faster and more efficient combustion, even under lean fuel conditions. This feature is particularly advantageous for increasing engine efficiency and reducing NOx emissions.

Moreover, hydrogen exhibits a broad flammability range, from 4% to 75% by volume in air [2], which facilitates stable combustion across a wide range of air-fuel mixtures. This flexibility is essential in dual-fuel systems where the primary fuel (ammonia, in this case) requires an ignitable and supportive co-fuel to maintain consistent combustion. However, hydrogen's low ignition energy and high propensity for pre-ignition present potential safety risks and require precise control during fuel injection and ignition timing.

2.3 Ammonia-Hydrogen System in Internal Combustion Engines

The NH_3/H_2 approach employed in this project capitalizes on the complementary properties of ammonia and hydrogen. Hydrogen's rapid ignition and wide flammability range effectively mitigate ammonia's low flame speed and high ignition temperature, resulting in a more stable combustion process. In this setup, hydrogen is port-injected to create a pre-mixed, ignitable charge, while ammonia is continuously dosed into the intake air using a proportional valve.

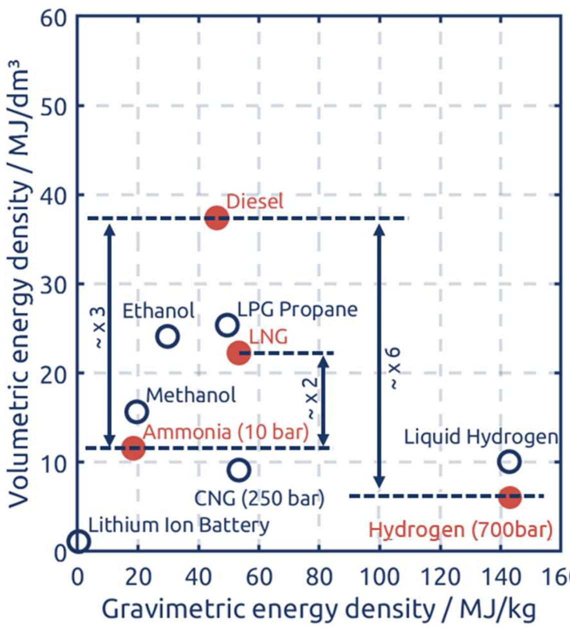

Figure 1. Volumetric and gravimetric energy density of ammonia and hydrogen in comparison to conventional fuels

This configuration allows the engine to maintain a stable and efficient combustion regime, achieving power outputs comparable to conventional fuels while significantly reducing CO_2 emissions.

By optimizing the fuel mixture, injection timing, and spark ignition, this project demonstrates a feasible ammonia-hydrogen combustion process that addresses many of ammonia's inherent combustion limitations. This technology is particularly relevant for maritime applications, where storage and handling of large fuel quantities are feasible, and where stringent emissions regulations incentivize the adoption of carbon-neutral fuels.

In summary, the combined properties of ammonia and hydrogen make them a viable fuel pair for combustion engines, particularly in applications that prioritize emissions reduction and operational efficiency. The insights gained from this project contribute to the broader knowledge base on alternative marine propulsion systems and showcase the potential for ammonia-hydrogen fuel systems to support carbon-neutral energy solutions across the maritime and transport sectors.

Similar approaches could be found in [11-15], though, mostly focusing on low H2 admixture rates and different engine sizes as well as combustion concepts.

3 EXPERIMENTAL SETUP

3.1 Engine test-bench

3.1.1 Fuel infrastructure and safety

3.1.1.1 Hydrogen – The hydrogen infrastructure is a 3-level system. In the first level hydrogen is stored either in gas cylinder bottles or in a trailer at 300 bar respectively 200 bar. For distribution within the laboratory (second level), the hydrogen is expanded down to 60 bar (and could optionally be compressed up to 500 bar for high-pressure H_2-applications). In the third level, the final application hydrogen pressure is precisely regulated using pressure regulators within each test-bench. Each level is monitored and equipped with pressure relief valves in order to evacuate in-between engine operation.

Several hydrogen gas sensors are installed at the test-bench to monitor potential gas leaks above the engine, at the exhaust air fan, in the exhaust path and in the engine's blow by. If a limit value of 50% lower explosion limit is exceeded, the test cell controller directly controls the test-bench ventilation, fuel supply and injection cut-off and optionally flushes the crank-angle case with nitrogen.

3.1.1.2 **Ammonia –** Ammonia is stored in gas bottles at 8.6 bar with immersion tube. The ammonia gas bottles are stored within a separate gas cylinder cabinet which contains shut-off valves, heat exchanger, pressure regulator as well as measurement equipment for pressure, temperature, mass flow, Figure 2. The cabinet is placed inside the engine test-bench and constantly vented when ammonia bottles are inside. Furthermore, the cabinet as well as the engine test-bench are equipped with ammonia sensors to detect leakages.

The ammonia is extracted in liquid phase using the bottles immersion tube. The liquid phase is ensured by cooling the ammonia with water at 10°C before its mass flow is measured. Afterwards, the ammonia is evaporated using a heat exchanger that is connected to the engines hot cooling water. Finally, the ammonia pressure is reduced to the application's specification. In order to evacuate the ammonia pipes, ammonia can be blown off in a controlled manner via a throttle to prevent emission limit values from being exceeded.

3.1.2 Measurement equipment

The engine test-bench is equipped with a test-bench automation system (AVL PUMA) for engine monitoring and control of subsystems (ventilation, fuel supply, cooling water, etc.). For measurement of H_2 and NH_3 consumption, Siemens Sitrans FC Mass 300 respectively FC Mass 2100 has been used.

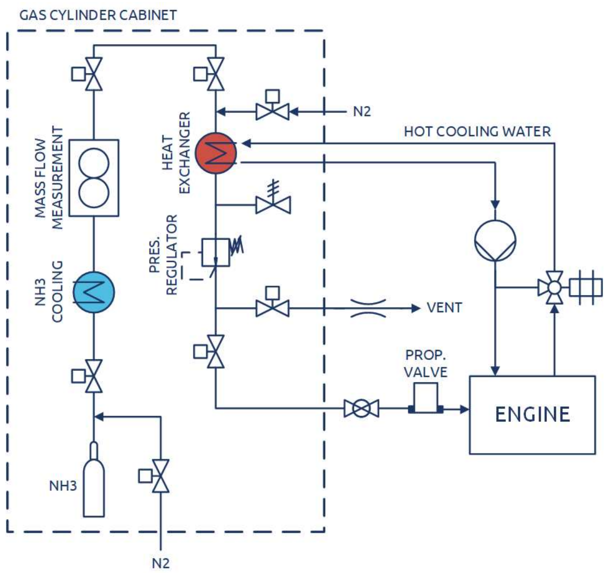

Figure 2. Layout of the ammonia module

In order to record in-cylinder pressure traces a Kistler KiBox indication system has been used with 6041B pressure sensors installed at each cylinder and 4075A sensor for intake pressure measurement. Besides recording in-cylinder pressure traces for post-test analysis of the combustion process, it was also used for online detection of combustion anomalies like pre-ignition, backfire or knocking.

3.2 Cracker

The ammonia cracker module (Figure 3) is used for onboard hydrogen production from ammonia by means of a fixed bed reactor in which the ammonia is catalytically cracked by adding heat. The catalytic reaction reduces the heat requirement of the real reaction, which is shown in equation 1 under idealized reference conditions, and enables a higher conversion of ammonia into hydrogen- and nitrogen-containing cracker product gas (CPG) at the same applied conditions.

$$2\ NH_3 \rightarrow 3\ H_2 + N_2,\ \Delta h_R^0 = 45.9\ \frac{kJ}{mol_{NH_3}} \quad (1)$$

According to Le Chatelier's principle [9] or the principle of least constraint, the real equilibrium of an applied reaction can be shifted accordingly by increasing the temperature, reducing the pressure or lowering the product concentration. According to the reaction equation (eq. 1), the product gas of the ammonia cracker ideally consists of 75 mol% hydrogen and 25 mol% nitrogen. As a consequence, the residual ammonia content in the product depends, among other things, on the reaction temperature, the pressure and the space velocity of the ammonia volume flow in the reactor.

The cracker system essentially consists of various supply lines (ammonia, propane, nitrogen), the cracker module with catalytic fixed-bed reactor, a propane burner, several internal heat exchangers and a control system. The cracker is supplied with gaseous ammonia via an ammonia supply line. The pressure is set to 4 bar via a pressure control unit. The ammonia is then preheated via internal heat exchangers before it enters the actual reactor. In the reactor, the ammonia is catalytically split into the product gas. The product gas is cooled via internal heat exchangers and then supplied to the engine. The heat exchangers are interconnected to increase efficiency. The heat required for the endothermic reaction is provided by a propane burner.

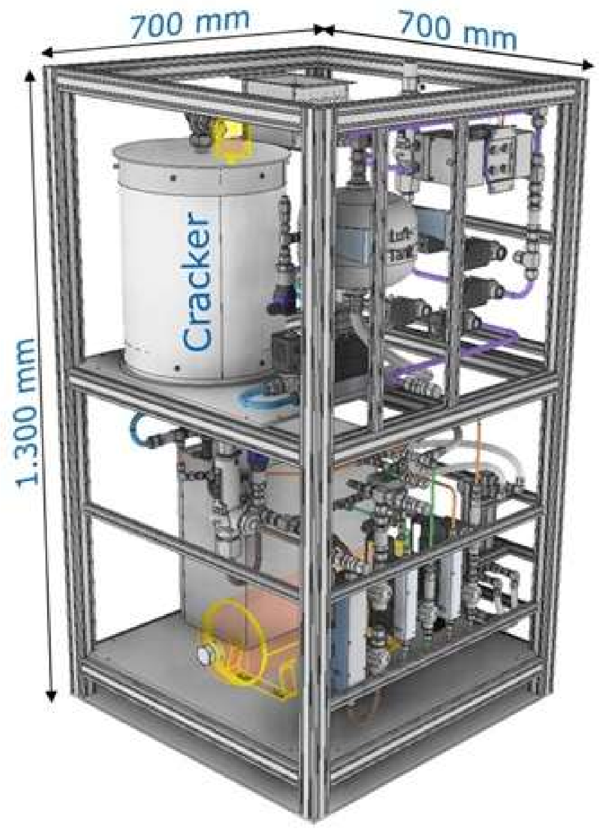

Figure 3. Ammonia cracker

The ammonia cracker system was designed and optimized to produce a chemical power of 8 kW hydrogen, with the required heat supplied by a burner located inside the cracker reactor. For safety purposes, a propane flame is used for combustion instead of the hydrogen-rich product gas or ammonia, ensuring reliable flame monitoring.

The development of safety strategies was crucial for the mobile and autonomous cracker system.

The main emphasis was placed on primary explosion protection through object removal and purging. This approach incorporates functional safety measures for monitoring and shutdown, along with an operational control system that manages complex startup, coupling procedures, and regular maintenance checks. Emergency shutdown is achieved by nitrogen purging, which guarantees a safe state under any circumstances. The system complies with occupational safety standards for both test benches and laboratory setups, as well as with the relevant regulations for fired process plants.

3.3 Engine

As test engine a 3.6 litre LPG engine has been used, Table 2. In order to run with H_2 (respectively

CPG) and NH_3, the fuel injection system of the engine had to be modified. The modified engine uses two separate fuel injection systems, one for H_2/CPG and one for NH_3. Figure 4 illustrates the structure of the injection system. Hydrogen / CPG is injected using Keihin port-fuel injectors with a pressure up to 2 bar. The aimed engine output of 15 kW can be reached by H_2-only operation. However, as the cracker's H_2 output is 8 kW, it was necessary for the yard application to add uncracked NH_3 to the combustion. This was done via dosing NH_3 into the intake path with the help of a proportional valve.

Table 2. Specification of test engine

Characteristic	Value	Unit
Displacement	3.6	L
Cylinder	4	-
Engine type	Spark-ignited	-
Mixture formation	Port fuel & continuous single point injection	-
Bore	98	mm
Stroke	120	mm
Compression ratio	11.5	-
Rated speed	2,300	min-1
Engine control unit	Trijekt premium	-

As this setup fundamentally differs from the original LPG setup it was necessary to switch from the engine's original engine control unit with limited access to an open engine control unit able to control both injection systems and communicate with other subsystems in the later yard application. For this reason, a Trijekt Premium ECU [10] has been chosen. In this context, the wiring harness must also be reassembled.

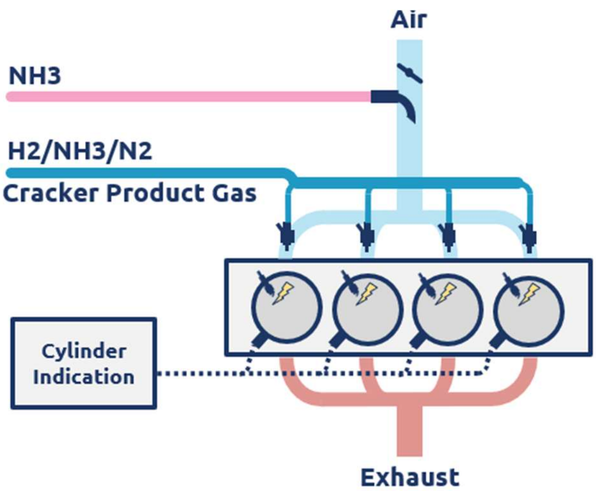

Figure 4. Schematic diagram of test engine

In H_2-only operation H_2 could be detected in the crankcase due to blow by gases during combustion. A nitrogen dilution system was implemented at the crankcase to avoid H_2 concentrations above lower explosion limit if needed.

4 RESULTS

4.1 H_2-only engine operation

In a first step, the engine was operated with pure hydrogen and the combustion was analyzed with various parameter variations at steady-state conditions. Figure 5 illustrates the combustion at varying combustion-air ratio while intake pressure was kept constant. The center of combustion was kept constant via adapting the ignition timing.

The rate of heat release shows a typical spark-ignited combustion. Due to the increase of hydrogen injected, engine output power increases as shown in the higher cumulated heat release at the end of combustion. The lower the air-fuel ratio, the higher the maximum rate of heat release as more chemical energy is introduced, Figure 6. It can be seen, that for lower air-fuel ratios the hydrogen-air-mixture burns faster.

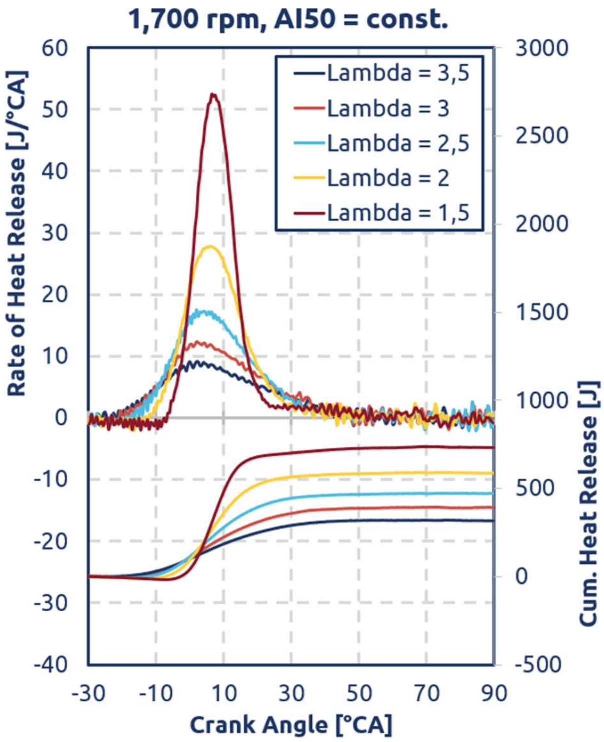

Figure 5. Pure hydrogen operation at 1,700 rpm, AI50 = 8 °CA, p_H₂ = 1.25 bara, p_IN = 620 mbara

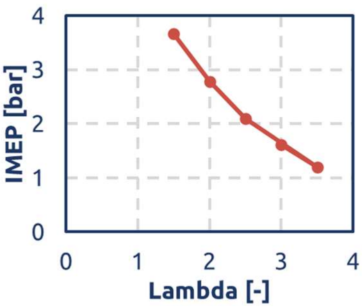

Figure 6. Impact of lambda on IMEP at 1,700 rpm, AI50 = 8 °CA, p_H2 = 1.25 bara, p_IN = 620 mbara

Figure 7 illustrates the dependency of combustion delay and cyclic variability (COV_imep) on ignition timing. It can be stated that a shift of the ignition angle to late leads to increased combustion delays and less steady engine operation (increased COV_imep). However, the impact of ignition timing is less apparent when air-fuel ratio is low.

4.2 H_2-NH_3 engine operation

In a second test row, ammonia has been admixed into the intake path to see the impact on combustion. Pure ammonia spark-ignited combustion is rather unlikely due to its laminar flame speed, narrow ignition limits and high ignition energy (8 mJ vs. 0.14 mJ gasoline [1]). However, hydrogen can act as an ignition aid.

Figure 8 shows the rate of heat release in dependency of the admixed ammonia ratio. The ammonia ratio is related to the energy content admixed. During this test series mean effective pressure, air-fuel ratio, ignition timing as well as intake pressure have been kept constant. The admixture of ammonia clearly slows down the combustion leading to a decreased maximum heat release.

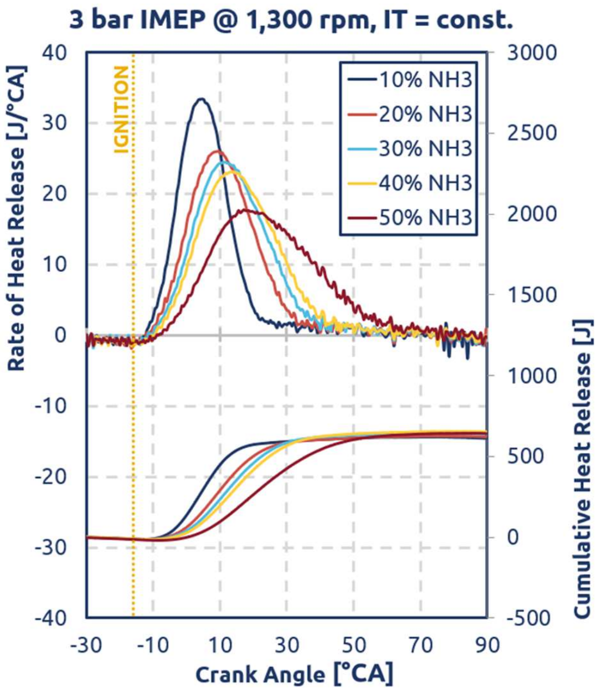

Figure 8. Impact of ammonia admixture to hydrogen combustion at 1,300 rpm, imep = 3 bar, p_H_2 = 1.25 bara, IT = -16 °CA, lambda = 2, p_IN = 620 mbara

As Figure9 illustrates, the lower flame speed of ammonia leads to prolonged combustion durations, thus retarded combustion center and increased combustion delays. As a result, engine efficiency decreases, and exhaust temperatures rise. Furthermore, the admixture of ammonia leads to increased cyclic variability, as can be seen by the rising coefficient of variance of indicated mean effective pressure (COV_imep).

At constant center of combustion (IT adapted) the analysis of ROHR shows the increase in burning duration due to the admixture of ammonia without overlapping effects from the retarded combustion, Figure 10. Maximum heat release is reduced when ammonia ratio increases.

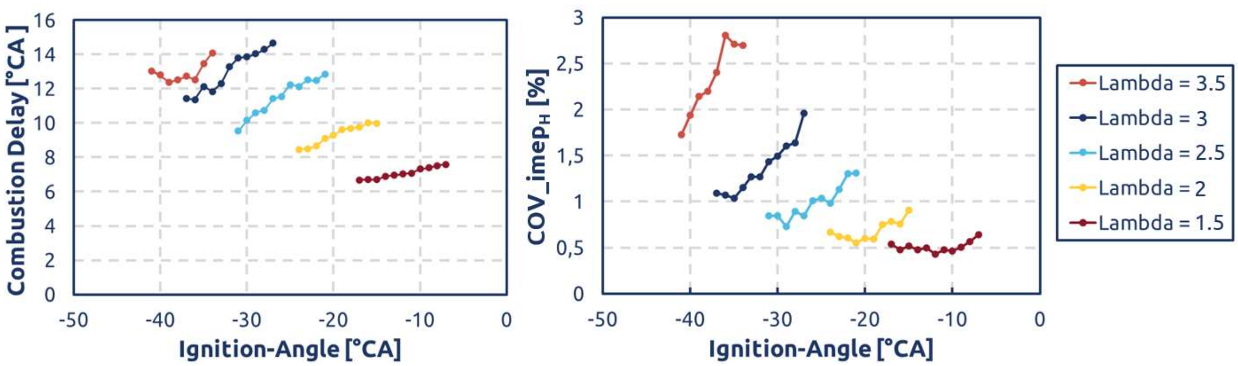

Figure 5. Combustion delay and cyclic variability in dependency of ignition angle in pure hydrogen operation at 1,700 rpm, AI50 = 8 °CA, p_H2 = 1.25 bara, p_IN = 620 mbara

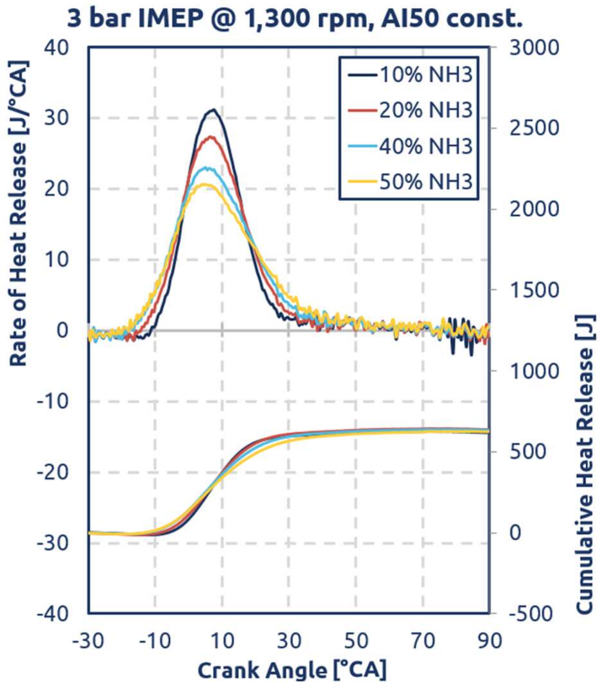

Figure 10. Impact of ammonia admixture to hydrogen combustion at 1,300 rpm, imep = 3 bar, p_H_2 = 1.25 bara, AI50 = 8 °CA, lambda = 2, p_IN = 620 mbara

Figure 11 shows an early shift of the 5% energy conversion point due to the adapted injection timing. However, even with constant center of combustion, combustion delay increases as a result of the higher ignition temperature of ammonia. Maximum in-cylinder pressure slightly decreases due to the slower combustion. Again, the admixture of ammonia increases cyclic variability (COV_imep) due its worse combustion properties.

As another result, the admixture of ammonia shifts the knocking limit in comparison to the pure hydrogen combustion. Knocking limits engine efficiency as spark-ignited engines tend to undesired pre-ignition at early ignition timing. Due to the ammonia share it was possible to increase the mean effective pressure by 32 % while knocking peak remained constant, Figure 12 and Figure 13.

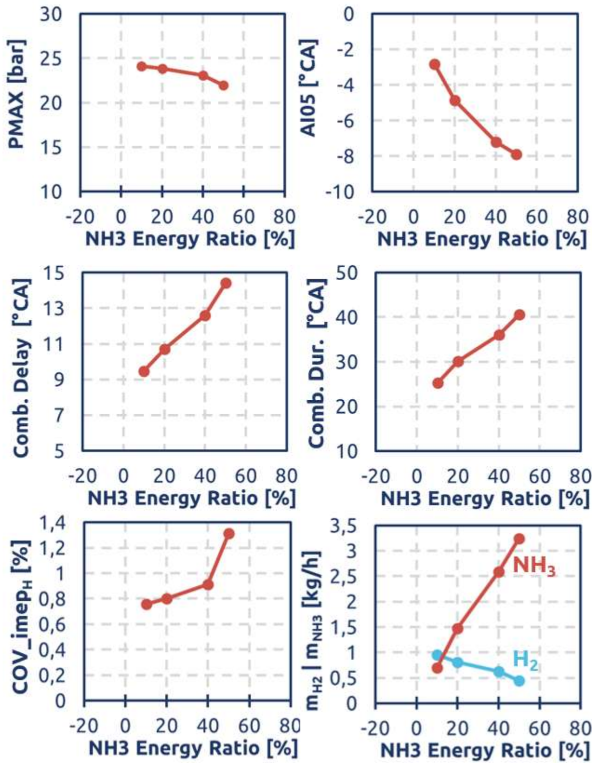

Figure 11. Impact of ammonia admixture on combustion at 1,300 rpm, imep = 3 bar, p_H_2 = 1.25 bara, AI50 = 8 °CA, lambda = 2, p_IN = 620 mbara

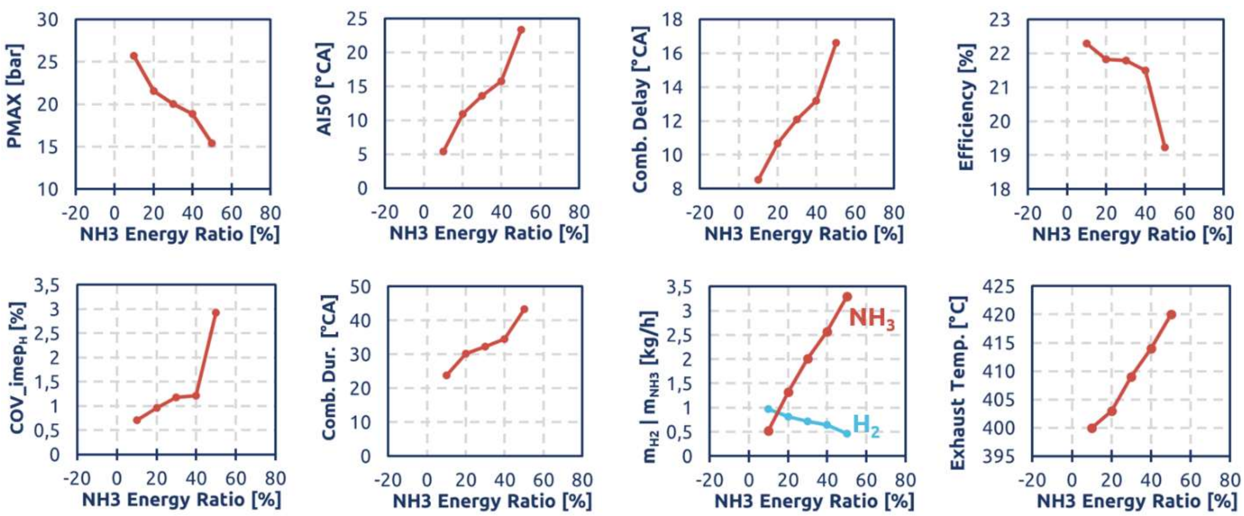

Figure 9. Impact of ammonia admixture on combustion parameters at 1,300 rpm, imep = 3 bar, p_H_2 = 1.25 bara, IT = -16 °CA, lambda = 2, p_IN = 620 mbara

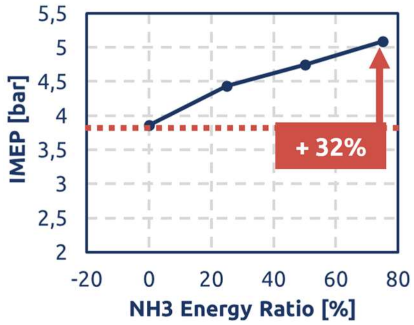

Figure 12. Potential of imep increase due to knock-resistant ammonia admixture at 1,000 rpm, lambda = 2

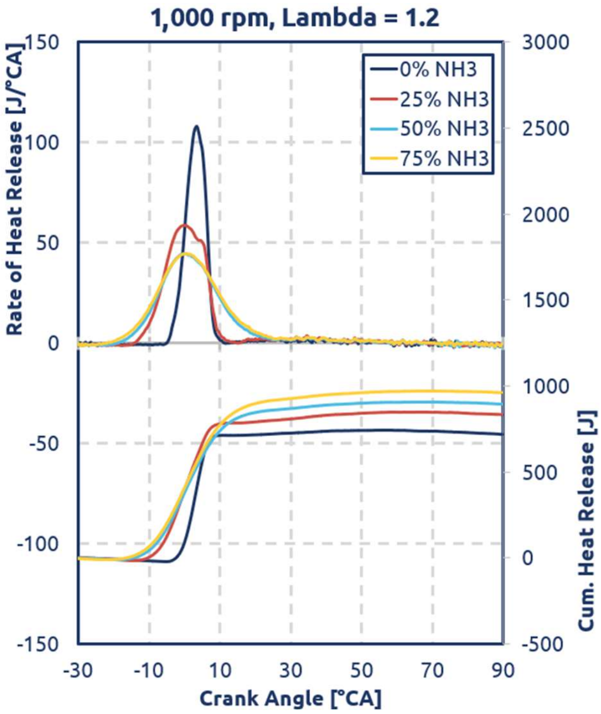

Figure 13. Heat release rate at 1,000 rpm with adapted IT to remain constant knocking peak

4.3 Engine-cracker operation

For the final yacht application, the engine's hydrogen feed is produced by the onboard cracker system. As explained in section 3.2, the cracker product gas differs slightly from pure hydrogen gas as used in the experiments in section 4.1 and 4.2.

Before installing onboard the yacht, cracker and engine were tested at engine test bench. This included both steady-state tests as well as engine start tests. Due to the limited cracker output, only idling and low load conditions are possible without ammonia admixture. Therefore, pure hydrogen and CPG combustion were compared at idle conditions. The significant nitrogen content and residue ammonia fractions in the cracker product gas retard the combustion. Therefore, ignition timing had to be adapted from -18 °CA with pure hydrogen to -24 °CA with cracker product gas. With this adaption, combustion progression of pure hydrogen and cracker product gas operation is very similar, Figure 14.

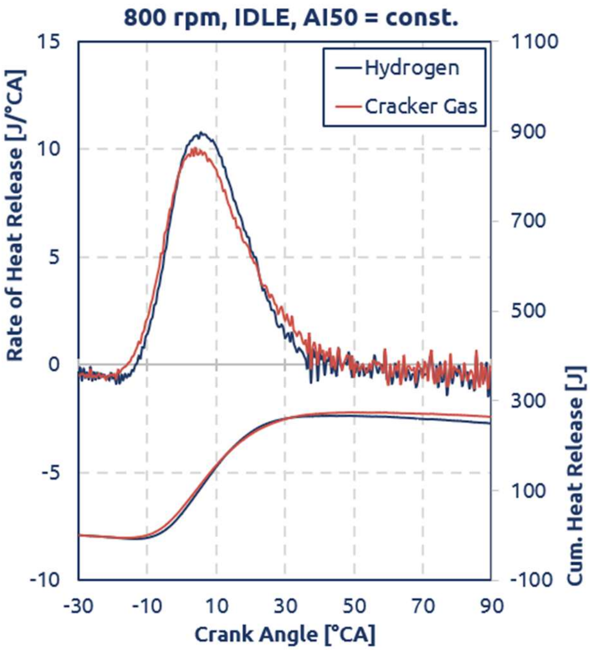

Figure 14. Comparison of pure hydrogen and cracker product gas combustion at idle conditions

For the final yacht application, comprehensive cracker-engine tests were performed to develop all relevant engine maps, like ignition timing or NH_3 admixture, for a stable and secure engine operation. During engine start and idling the engine runs entirely on cracker product gas. When a load request is sent by the yacht's control lever additional ammonia is admixed to the CPG combustion.

Thus, the engine runs at highly different NH_3/H_2-ratios throughout the engine map. Figure 15 illustrates the desired NH_3 mass flow map while cracker product gas mass flow is rather constant over the entire engine map. Thus, the engine dynamic depends directly on the admixed ammonia while the cracker product gas acts like an ignition fuel. Figure 15 shows that with increasing throttle position, respectively yacht control lever position, the desired NH_3 mass flow increases to deliver the desired chemical energy into the engine. At 1,900 rpm, NH_3 mass flow is reduced similar to a speed limiter. The limiting factor is, however, cyclic variability as NH_3/H_2 ratio is too high for stable engine operation. A higher cracker output in a follow-up project could stretch this limit.

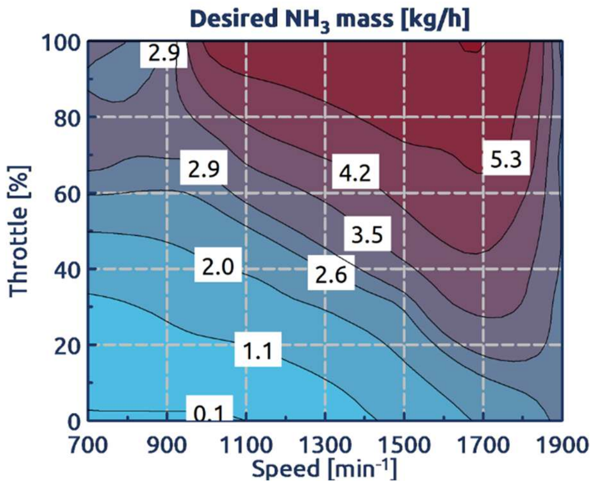

Figure 15. Final applied desired NH_3 mass flow map

5 YACHT IMPLEMENTATION

As part of the Campfire 07 project a sailing yacht has been manufactured by the project partners. This sailing yacht, called “Ammonia Sherpa” will be a swimming test vehicle for testing an optimizing ammonia-driven powertrains, Figure 16. As part of that the cracker and the test engine were installed onboard the ship. Besides that, a comprehensive ammonia storage and vaporization system, an ammonia driven solid oxide fuel cell and an ammonia mitigation system were implemented as well. These systems substitute the conventional powertrain and are controlled by a master PLC system.

Figure 16. "Ammonia Sherpa" experimental yacht

The engine was connected to a sail drive system and had to be adapted for maritime application (2-circuit sea water cooling system, wet exhaust system, etc.). Figure 17 shows the installed engine onboard the yacht with the connected sail drive which acts as one of the engine mounts.

Figure 17. Installed engine and sail drive onboard the yacht

6 SUMMARY

The results shown in this paper were developed within the "Campfire 07" project which investigates the application of ammonia (NH_3) as a viable alternative fuel. Within the project we developed and tested an ammonia-based powertrain capable of generating hydrogen onboard via a catalytic thermal cracker. Hydrogen is subsequently used as an ignition fuel in a modified spark-ignited internal combustion engine. The system was tested under laboratory conditions and was subsequently installed onboard a sailing yacht, demonstrating its potential as a low-carbon solution for maritime applications.

Ammonia is a carbon-free compound, making it attractive for reducing CO_2 emissions when produced from renewable sources. Its ability to serve as a hydrogen carrier simplifies hydrogen transportation and storage compared to conventional compressed or liquefied hydrogen gas. However, ammonia’s combustion properties - including a high ignition temperature, low flame speed, and narrow flammability range - pose significant challenges for stable combustion in traditional engines. These limitations are addressed in the project by pairing ammonia with hydrogen, a fuel with complementary properties, such as high flame speed and wide flammability range.

Hydrogen is injected into the intake air through PFI, while ammonia is added via controlled dosing. This configuration ensures a stable and efficient air-fuel mixture, leveraging hydrogen’s rapid ignition characteristics to overcome ammonia's slow combustion properties.

Initial tests with hydrogen-only combustion showed efficient and stable operation. Increasing the hydrogen injection rate improved power output, while adjustments to ignition timing reduced combustion delays and cyclic variability. The broad flammability range and high flame speed of hydrogen contributed to fast and complete combustion.

When ammonia was introduced into the intake path, its slower flame speed and higher ignition temperature resulted in prolonged combustion durations and increased cyclic variability. However, the addition of ammonia increased knock resistance, allowing for higher mean effective pressure without knocking. The NH_3/H_2 configuration effectively balanced the complementary properties of ammonia and hydrogen, achieving stable combustion.

The ammonia cracker successfully produced a hydrogen-rich mixture for engine operation. Tests revealed that the use of CPG, containing residual ammonia and nitrogen, required adjustments to ignition timing for stable combustion. Despite these challenges, the integrated cracker-engine system proved feasible, demonstrating consistent performance across varying loads and fuel ratios.

The culmination of the project was the deployment of the powertrain on the "Ammonia Sherpa", a sailing yacht designed as a test platform for ammonia-driven powertrains. The engine was adapted for marine use, including a seawater cooling system and wet exhaust.

The "Campfire 07" project demonstrates the viability of ammonia-hydrogen dual-fuel systems for carbon-neutral energy solutions, particularly in maritime applications. By addressing ammonia's combustion challenges with hydrogen as a co-fuel and leveraging onboard hydrogen generation, the project showcases an innovative pathway to sustainable propulsion. The results contribute to the broader understanding of alternative fuels and provide a foundation for future advancements in low-emission transportation technologies.

7 OUTLOOK

The next step is to commission the ammonia-powered sailing yacht with its innovative propulsion system. Once safe and stable operation of the yacht has been achieved, the yacht will be used to carry out field trials as part of test runs. These will identify new challenges and potential for improvement and aim to optimize engine operation and the overall system.

For this purpose, engine maps are adapted and the interaction of the individual subsystems on board the yacht is further optimized under real application conditions. In addition to stationary tests, transient load steps and engine start and stop tests are also carried out. The measurements are supplemented by online exhaust gas measurements.

8 ABBREVIATIONS

LPG: liquid petroleum gas

H_2: hydrogen

NH_3: ammonia

CPG: cracker product gas

AI05: position of 5% energy conversion

AI50: center of combustion

IT: ignition time

IMEP: indicated mean effective pressure

ROHR: rate of heat release rate

p_H_2: hydrogen injection pressure

p_IN: intake air pressure

Lambda: air-fuel ratio

COV: coefficient of variance

PMAX: maximum in-cylinder pressure

CD: combustion delay

PLC: programmable logic controller

ICE: internal combustion engine

PFI: port fuel injection

9 ACKNOWLEDGMENTS

This work was supported by Federal Ministry of Education and Research in the project "WIR! – CAMPFIRE – Entwicklung seines Funktionsmusters einer Ammoniak-betriebenen Segelyacht mit Hybridsystem aus Brennstoffzelle und Motor", sub-project: "Entwicklung eines Wasserstoff-/Ammoniak-Motors" (CF07_6, project ID: 03WIR2309F). We would like to thank our project partners INP Greifswald, HanseYachts AG, Autosoft GmbH, new enerday GmbH, IKEM e.V., and ISC GmbH & Co. KG for the successful cooperation.

10 REFERENCES

[1] Kobayashi et al. „Science and technology of ammonia combustion“, Proceedings of the Combustion Institute 2019, 37:109-133

[2] Gupta B. R. „Hydrogen fuel production, transport and storage“, CRC Press, 2008

[3] Liu et al. „Ammonia as a Fuel for SI Engine“, SAE Technical Paper 2003, 2003-01-3095

[4] Kong et al. „Developing Fuel Injection Strategies for Using Ammonia in Direct Injection Diesel Engines“, 2012, NH_3 Fuel Association

[5] Luther, H. „Dieselkraftstoff – das Problem unserer Tage“, Agrartechnik 2(2), 1952

[6] Merker et al. „Grundlagen Verbrennungsmotoren“, 2014

[7] https://encyclopedia.airliquide.com/methane

[8] P.J. Linstrom and W.G. Mallard, Eds., NIST Chemistry WebBook, NIST Standard Reference Database Number 69, National Institute of Standards and Technology, Gaithersburg MD, 20899, (retrieved March 5, 2019).

[9] Knox, Kerro. "Le Châtelier's Principle." Journal of Chemical Education 62.10 (1985): 863.

[10] https://trijekt.de/produkte/trijekt-premium/

[11] Dinesh, M. H., Jayashish Kumar Pandey, and G. N. Kumar. "Study of performance, combustion, and NOx emission behavior of an SI engine fuelled with ammonia/hydrogen blends at various compression ratio." International Journal of Hydrogen Energy 47.60 (2022): 25391-25403.

[12] Dinesh, M. H., and G. N. Kumar. "Effects of compression and mixing ratio on NH3/H2 fueled Si engine performance, combustion stability, and emission." Energy Conversion and Management: X 15 (2022): 100269.

[13] Mei, Bowen, et al. "Enhancement of ammonia combustion with partial fuel cracking strategy: Laminar flame propagation and kinetic modeling investigation of NH3/H2/N2/air mixtures up to 10 atm." Combustion and Flame 231 (2021): 111472.

[14] Reggeti, Shawn, Seamus Kane, and William Northrop. "Experimental investigation of spark-assisted compression-ignition with ammonia-hydrogen blends." Journal of Ammonia Energy 1.1 (2023).

[15] Lhuillier, Charles, et al. "Experimental study on NH3/H2/air combustion in spark-ignition engine conditions." 11th mediterranean combustion symposium. 2019.