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Ammonia as carbon-free fuel for maritime applications – combustion investigations and safety aspects

Basic research & advanced engineering - new concepts

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ABSTRACT

Carbon-free fuels are one of the options to fulfill the challenging GHG reduction targets adopted by the IMO in July 2023. MAN Energy Solutions as a leader for propulsion technology is committed to support customers in their need to achieve this target by providing dedicated products. This paper highlights different carbon-free and carbon-neutral fuels by comparing their general suitability for marine and power applications, respectively. Furthermore, this paper focusses on the comparison of future price development and availability and discusses the feasibility of marine applications powered by ammonia and thereby features details about MAN Energy Solutions' development in the four-stroke segment.

Fundamental investigation results using a rapid combustion and expansion machine (RCEM), including optical measurements, are shown. These results characterize the ammonia combustion process and explain the challenges with ammonia due to its poor combustion properties, when compared to e.g., methanol. Based on these results a combustion model was developed, further showcasing that the developed combustion model is in good agreement with measurements. Single-cylinder engine results that meet stringent emissions and power output requirements are presented as well and the derived engine concept is described in the following, including the required exhaust aftertreatment technology. Thus, underlining the potential to reduce GHG by up to 90%, when compared with engines powered by carbon-based fuels like diesel or LNG.

Ultimately, a fuel and safety concept is being introduced, showing that the implementation, i.e. storage and supply, of ammonia on board a ship is possible, despite its toxicity. This concept was discussed with classes and achieved an approval in principle (AiP).

1 INTRODUCTION

In 2018 the IMO (International Maritime Organization) announced its initial greenhouse gas (GHG) reduction strategy with the goal to reduce the yearly GHG emissions until 2050 by 50% compared to 2008. In July 2023, with support from all IMO member states, a new GHG strategy was adopted, and the targets were tightened with the goal to be climate neutral in the year 2050. Figure 1 shows the adopted IMO strategy including the intermediate steps and targets.
The blue line shows the GHG emissions for the "business as usual scenario". The green line shows the new scenario adopted in 2023. The intermediate targets are the following:

In 2030 the GHG reduction shall be at least 20%, but striving for 30%, whereby the intensity (CO_2 per transport work) shall be reduced by 40%.
In 2040 the goal is a minimum of 70% GHG reduction, striving for 80% and finally
by 2050, net-zero GHG emissions shall be reached.
Regarding the calculation method for the GHG levels, a well-to-wake approach is to be considered, based on the IMO Life-Cycle-Assessment guidelines.

The new strategy's goals are ambitious and will lead to a variety of technical solutions in combination with various fuels. Among those, green methanol and green ammonia will be large contributors in achieving these targets in the future. Due to its properties, green methanol is a very suitable fuel for future new-built ships and even more so for retrofits [2]. Meanwhile, ammonia is moving more and more into the focus as another future fuel for good reasons. Ammonia is carbon free and consequently does not emit CO_2 when burned in an internal combustion engine. The production process of ammonia (Haber-Bosch) is well mastered on a large industrial scale and switching from blue to green ammonia does not require drastic changes to the production process. Simply the hydrogen sourcing for the production process will change from blue to green hydrogen, making blue ammonia also a perfect segway until green ammonia can be produced with green energy. This fact and the fact that green ammonia will be needed anyway in the future will increase the willingness to invest in ammonia production dramatically. Despite the fact that ammonia is one of the most produced chemicals already. Approximately 180Mt were produced in 2021 [3], of which 18-20Mt are transported each year [3], showing that handling ammonia is well-mastered. Furthermore, ammonia storage is less costly compared to hydrogen, another carbon free fuel, and therefore, emerges as a transport vector for hydrogen and as a means to transport energy from regions with a high potential for green electricity to regions with a great demand for energy [4]. For this reason, ammonia is seen a substitute for crude oil and LNG in the future. By summing up these advantages, yet not leaving out its drawbacks such as its toxicity and physical properties that do create challenges for its drop-in use in internal combustion engines, it is clear that ammonia will play a significant role in the maritime and power business of the future.
Note that the first MAN ES 2-stroke ammonia engine (S 60) was delivered to a yard in 2024. In general, the market interest for 2-stroke ammonia engines is at least for the moment much higher than for 4-stroke engines. This is not only due to the fact that most ammonia carrier ships are powered by 2-stroke engines, but also due to the planned future installation of green corridors for container ship applications, that are mainly propelled by 2-stroke engines.
In the following, ammonia is compared with other future fuels regarding fuel properties, expected future price development, and suitability as engine fuel in internal combustion engines. Furthermore, fundamental investigations of ammonia in a Rapid Compression Expansion Machine (RCEM) are described. Thereafter, the paper presents the results for the investigations in a 175 mm bore 4-stroke research engine and the modelling of ammonia combustion in a 3D CFD tool. The

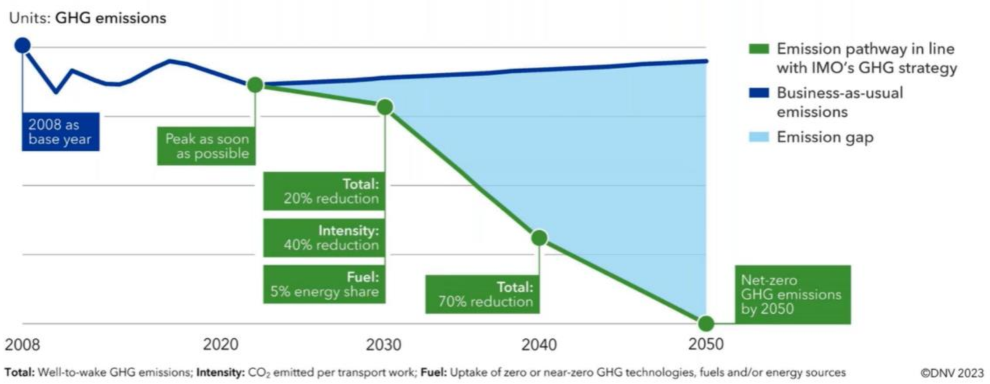


Figure 1. IMO GHG strategy adopted 07.07.2023 [1]

technical session will close with the description of the derived engine concept including important safety aspects for maritime applications.

2 AMMONIA AS MARITIME FUEL

2.1 Fuel properties of ammonia and comparison to other potential future fuels

For all long-distance remote applications without the possibility of refueling, the energy density of the energy source is of crucial importance. Figure 2 gives a comparison of different energy carriers with respect to their volumetric and gravimetric energy density.

The dots represent the physical properties, while the blue arrows in the diagram indicate the energy density including the tank volume and overall weight required for the storage of the specific fuel. It is obvious that Diesel and Diesel-like fuels set the benchmark regarding volumetric and gravimetric energy density. In extreme contrast, batteries are very poor regarding these criteria and are not suitable for long-distance applications. Only liquid fuels and liquefied gases are within reach of Diesel`s energy density. Another advantage of liquid fuels compared to batteries is the quick refueling process when compared to the loading process of batteries. In addition, batteries have high local electric energy demands during recharging.

Another important aspect is the future price development for these fuels. Figure 3 illustrates the expected price development [5] for production in southern European regions (indicated by the “S”). It is assumed that by 2050 the cost- and energy-intensive technology of direct air capture will be a legal requirement, at least in Europe. Thus, production prices in 2050 for carbon-based fuels remain close to their 2030-levels, whereas prices for non-carbon fuels, such as H_2 and NH_3, decrease towards 2050.

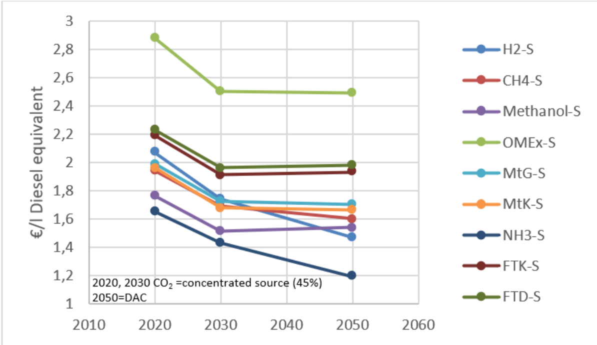


Figure 3. Forecast production price development for e-fuels (based on [5])

As mentioned above, the values in [5] assume that the fuels are produced in Europe. In the global maritime shipping industry, the transport costs for fuels are important and influence where fuels are produced most economically. Figure 4 gives a comparison of selected future marine fuels in terms of transport costs on a representative route from Oman to Japan, a distance of about 8000km.

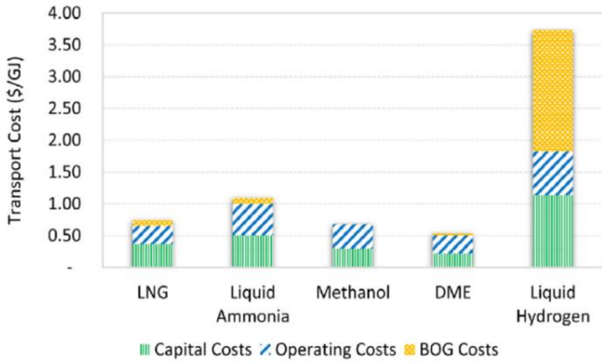


Figure 4. Transportation costs for future fuels from Oman to Japan [4]

When comparing the transportation costs of ammonia to that of hydrogen, as the only other carbon free fuel available, the advantages of transporting ammonia become clear.

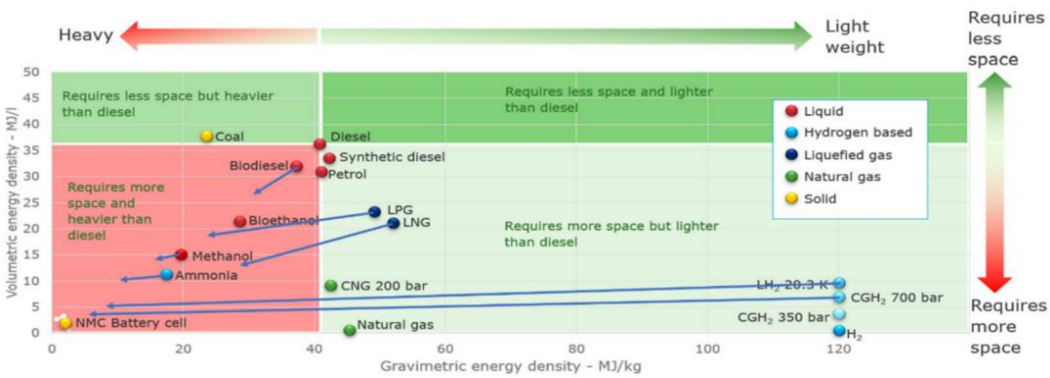
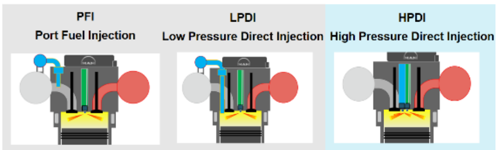


Figure 2. Comparison of gravimetric and volumetric energy density of different energy carriers [2]

Taking all these facts and figures into account, it becomes obvious that ammonia will reach a significant share in the future maritime fuel mix and will also be adopted for future power applications.

2.2 Fuel admission and combustion concepts for ammonia

In principle, both Otto-cycle and Diesel-cycle are suitable for burning ammonia. For Otto-cycle engines, ammonia can be injected in liquid or gaseous form upstream of the inlet valve using a Port-Fuel-Injection (PFI) system, or directly into the combustion chamber during the intake stroke with a Low-Pressure-Direct-Injection (LPDI) system. For the Diesel-cycle combustion process, injection of ammonia is realized with a High-Pressure-Direct-Injection system (HPDI), which injects ammonia directly into the combustion chamber. A pilot injection of a Diesel-like fuel is mandatory to initiate the combustion process due to the low cetane number (CN) of ammonia. Figure 5 illustrates the different combustion principles.



	PFI	LPDI	HPDI
Process MAIN	Otto	Otto	Diesel
Fuel MAIN	Otto-Fuel	Otto-Fuel	Otto-Fuel or Diesel Fuel
Ignition MAIN	Pilot	Pilot	Pilot
Process BACK-UP	Diesel	Diesel	Diesel

Figure 5. Fuel injection equipment, arrangement and combustion processes

This paper focuses on the HPDI combustion concept.

3 INVESTIGATIONS WITH AMMONIA

The investigations follow an integrated approach to develop a well-performing HPDI combustion process for ammonia. First, fundamental investigations in an optical rapid compression & expansion machine (RCEM) create a more fundamental understanding of the combustion process and provide validation data for spray and combustion CFD simulations. Next, the created understanding helps define promising configurations and operating conditions for the research single-cylinder engine (SCE) tests. The investigations on the SCE prove the high potential of ammonia HPDI to achieve low emissions combined with high engine performance and reveal future research and development needs. And ultimately, the development of a CFD code and its validation against RCEM and test engine data yields a tool capable of supporting future development efforts.

3.1 Combustion of ammonia in an optical RCEM

Experimental investigations at the Technical University of Munich (TUM) aim at establishing a fundamental understanding of ammonia HPDI combustion. For this purpose, an optically accessible RCEM featuring single-hole injectors for diesel and ammonia is used [9,10]. The RCEM allows varying operating conditions, injection parameters, and the geometrical injector arrangement. Furthermore, well-defined boundary conditions and quiescent charge conditions in the RCEM produce data for the validation of performed CFD simulations.

Figure 6 shows the RCEM's driving system and the injector arrangement in the cylinder head. Pressurized air propels the piston. However, its trajectory equals that of a real engine operating at 1000 rpm. Table 1 shows the RCEM's specifications and the operating parameters relevant for this section.

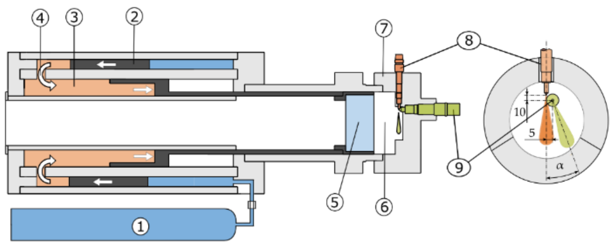


Figure 6. RCEM driving system and cylinder head: (1) driving-air bottles, (2) driving piston, (3) hydraulic fluid, (4) flow orifice, (5) working piston, (6) combustion chamber, (7) cylinder head, (8) diesel injector, (9) ammonia injector [9]

The data obtained during experiments include heat release rates, optical data, and exhaust gas compositions. Various optical measurement techniques, including spectroscopy, Mie-scattering, shadowgraph, OH*-chemi-luminescence, and natural flame luminosity imaging were used to characterize and understand the combustion process in detail. Among others, the optical data provides liquid penetration, gaseous penetration, flame front location, and heat release rates, which are key parameters for validating CFD simulations (see section 3.2).

Table 1. RCEM operating parameters

Bore diameter [mm]	220
Equivalent engine rpm [1/min]	1000
Effective compression ratio [-]	20.5
TDC temperature [K]	920
TDC pressure [bar]	125
Ammonia injection mass [mg]	210
Ammonia injection duration [ms]	2.7
Ammonia injection pressure [bar]	530
Diesel injection mass [mg]	5
Diesel injection duration [ms]	0.52
Diesel injection pressure [bar]	2000
Diesel start of injection [ms bTDC]	-2
Ammonia energy share [%]	90-95

Ammonia's physical and chemical properties are detrimental to its ignition and combustion behavior. For example, its high enthalpy of evaporation causes low temperatures within the fuel sprays. In addition, ammonia's low flame speed and high auto-ignition temperature may cause incomplete combustion.

Therefore, the initial investigations in the RCEM focused on examining and defining the conditions required for successful ignition and combustion of ammonia sprays. For this purpose, the effects of pilot mass and the spatiotemporal interaction between diesel and ammonia were investigated. *Figure 7* shows the corresponding results.

The temporal interaction is varied by shifting the ammonia injection timing, while keeping the diesel injection timing fixed at 2 ms before TDC. Negative relative injection timings indicate that ammonia is injected before diesel. Rotating the ammonia injector (see Figure 6) alters the spatial interaction between the diesel pilot injection and the ammonia main injection. Positive interaction angles (α) indicate diverging sprays, while negative interaction angles indicate converging sprays.

For the parameters mentioned above the relative fuel burnout rates for 10 mg diesel pilot injections (top), and 5 mg diesel pilot injections (bottom) is displayed. The plots include data from 149 experiments. 5 mg diesel pilot injections correspond to a 95% energetic share of ammonia. Dots indicate assessed combinations. The relative burnout rate is based on the cumulative heat release compared to the maximum cumulative heat release observed (obtained for the conditions indicated by the star). Dots in a white area indicate that the ammonia spray failed to ignite under the corresponding injection configuration. The maximum cumulative heat release results for slightly converging fuel sprays (-7.5°) and a slightly advanced diesel pilot fuel injection (+0.5 ms). These conditions enable undisturbed ignition of the pilot fuel followed by strong interaction with the ammonia spray and swift ignition thereof.

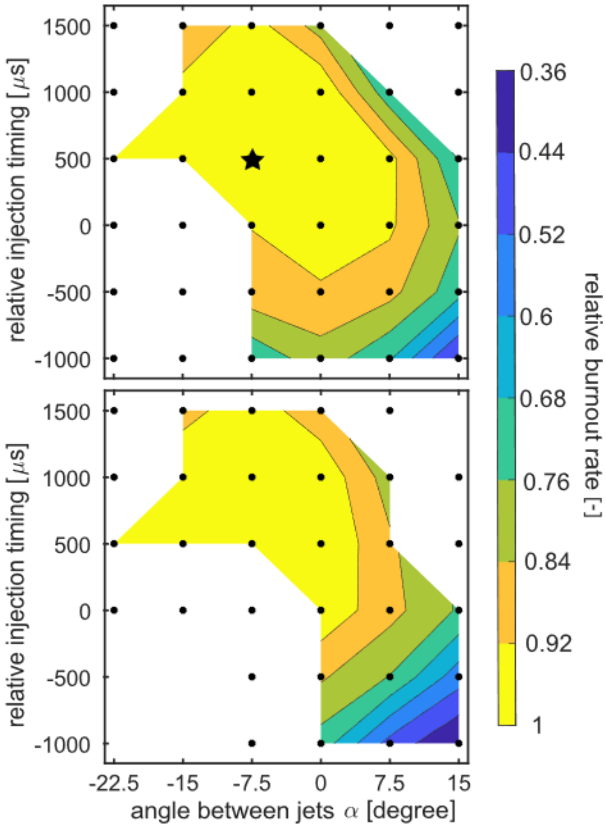


Figure 7. Relative burnout rate for different interaction angles α and relative injection timings for 10 mg (left) and 5 mg (right) diesel pilot injections [9]

In contrast, unfavorable interaction conditions may lead to incomplete combustion of ammonia or deteriorate diesel pilot ignition. For example, injecting ammonia before diesel and supplying the diesel pilot injection into the cold ammonia spray (bottom left corners of the plots in Figure 7) supresses pilot fuel ignition entirely. In contrast, injecting the pilot fuel long before ammonia with diverging spray angles (top left corners of the plots in Figure 7) enables undisturbed pilot ignition. However, the ammonia spray fails to ignite since the interaction with the diesel combustion products is too weak. The results show that the thorough ignition and combustion of ammonia sprays via diesel pilot injections requires a carefully designed injection concept.

Furthermore, the optical access of the RCEM enables deeper insight into the combustion process. The simultaneous imaging of density gradients via shadowgraph imaging and the flame via OH*-chemiluminescence imaging effectively visualizes mixture formation and combustion. *Figure 8* shows simultaneously acquired and superimposed shadowgraph and OH*-chemiluminescence images of an experiment with a slightly advanced 5 mg diesel fuel injection (+0.5 ms) and slightly converging sprays (-7.5°), i.e., well-performing conditions as described above.

First, diesel ignites and combusts without interacting with the ammonia spray (t=-196 µs and t=193 µs). Subsequently, the ammonia spray starts to interact with the diesel combustion products and ammonia combustion begins (see Figure 8, t=610 µs). At first, the ammonia spray itself is hardly distinguishable from the diesel spray, since the two sprays overlap strongly to achieve maximum interaction. However, the ammonia spray eventually penetrates through the diesel combustion products and becomes clearly visible (see Figure 8, t>610 µs). The reaction zone gradually drifts off from the injector nozzle towards the cylinder liner. However, even after the end of injection at t=2700 µs, the ammonia flame persists, and ammonia burns in a strongly lifted flame without requiring additional supply of pilot fuel (see Figure 8, t=2999 µs).

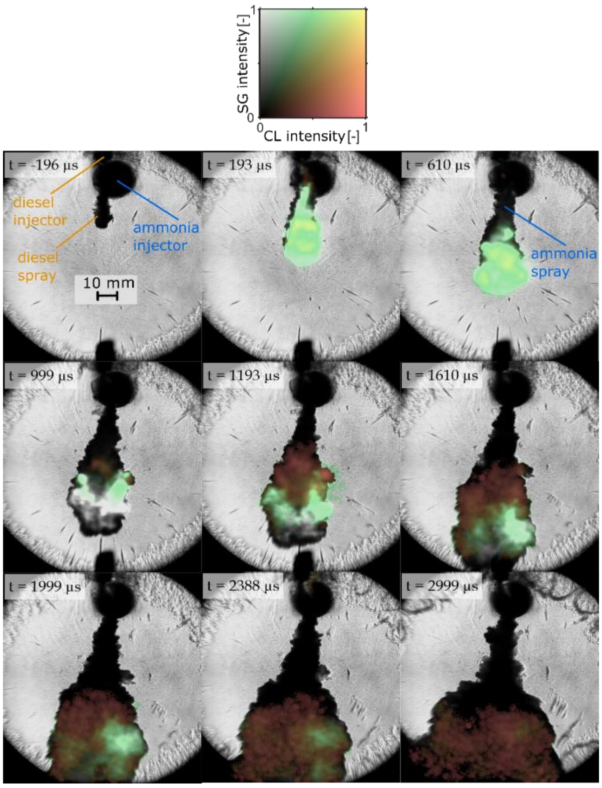


Figure 8. Simultaneously acquired, superimposed Shadowgraph and OH*-chemiluminescence images [10]

This drifting, non-stabilized flame behavior is discussed in detail in previous publications from TUM, e.g., [10]. They attribute the lack of a stabilized flame to ammonia's high mixing requirements with combustion products to undergo auto-ignition. CFD simulations of the RCEM experiments successfully replicate this drifting flame behavior and prove the importance of combustion products for ammonia spray combustion [11]. However, the CFD simulations using the RCEM setup also show that the ammonia flame completely stabilizes at ambient temperatures of 1100 K and above. At high temperatures, auto-ignition reactions of ammonia become more prominent, and the ammonia spray flame becomes less reliant on entrained combustion products. The RCEM does not achieve these higher temperatures required for flame stabilization since the pressure rise during combustion is low due to the single spray configurations employed. However, heavy-duty engines achieve the required temperatures.

In summary, the insights presented in this section suggest that ammonia sprays in engines should be ignited by intense interaction with a pilot fuel injection. The pilot fuel must be injected before ammonia for undisturbed ignition. Then, the combustion products created during pilot fuel combustion and early ammonia combustion assist ammonia spray combustion. Before yet, as in-cylinder pressures and, therefore, in-cylinder temperatures rise during combustion, ammonia spray flames stabilize and thus promote complete combustion.

3.2 Simulation of ammonia combustion

This section briefly summarizes the step-by-step development and validation process for ammonia-diesel dual-fuel combustion simulation. Optical investigations of the RCEM were used to validate diesel and ammonia spray simulations for a wide range of pressure conditions [12]. The spray simulations showed excellent agreement with the experimental data. Based on the validated sprays, a previous publication [13] compares tabulated and complex chemistry approaches to model ammonia-diesel DF combustion. The tabulated chemistry approach proved unable to predict the combustion behavior correctly. As soon as ammonia fuel interacts with diesel combustion products, ammonia combustion immediately begins. This is due to model limitations of the investigated ECFM-CLEH model. Furthermore, predicting misfiring events (white areas in Figure 7) with the tabulated chemistry approach was not possible.

However, when using a complex chemistry approach and a suitable chemical mechanism developed by TUM, it is possible to correctly predict the combustion of ammonia and reproduce misfiring events in the RCEM [13].

The following section shows the transfer of the developed and validated simulation approach from the RCEM to engine applications. First of all, it was investigated if the reproduction of the single-cylinder experiments is possible. Section 3.3 describes in detail the FM18 research engine that delivers the experimental data. The interaction angle of the diesel and ammonia sprays replicate the findings of the RCEM to provide favorable combustion conditions. The simulative setup uses complex chemistry with a chemical mechanism developed by TUM. The injection rates are based on experimental measurements conducted by Woodward L'Orange (WLO). Furthermore, the meshing of the simulation domain includes a two-staged refinement to resolve the fuel sprays (Figure 9).

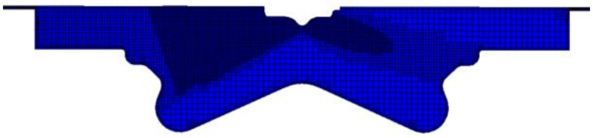


Figure 9. Mesh used for the FM18 combustion simulations with two-staged mesh refinement

The validation of the simulative combustion prediction for high speed boundary conditions was carried out at the nominal engine speed of 1800 rpm at 75% engine load.

Three different combustion scenarios are considered: a reference case (Case 1) with diesel pilot injection shortly before ammonia injection, a case with late diesel pilot injection after some of the ammonia has been injected (Case 2), and a case with early diesel pilot injection (Case 3).

Figure 10 compares the cylinder pressure of the experiment and the simulation for all three test cases. The SOI variation has been conducted based on a successful charge exchange simulation for the reference case.

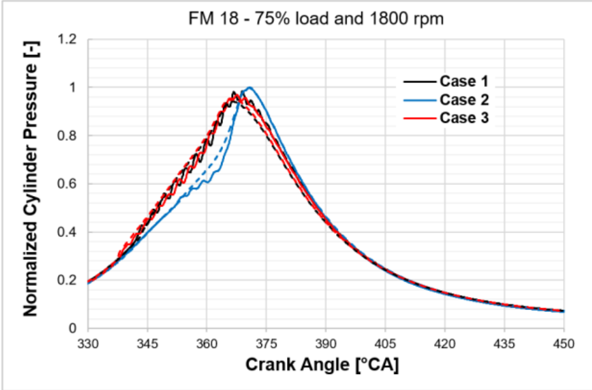


Figure 10. Normalized cylinder pressure of different combustion cases at 1800 rpm and 75% load, comparison of simulations (solid lines) and experiments (dashed lines)

The effects of early diesel pilot injection are small compared to the reference case with an almost simultaneous begin of injection. The pressure curve changes significantly for the late start of diesel pilot injection. The ammonia spray has enough time to partially premix with air. When the diesel pilot ignites this partially premixed air-fuel mixture, the combustion of the ammonia is significantly faster than the diffusive ammonia combustion in case 1 and case 3. The predicted cylinder pressure is in good agreement with the experimental data for all three investigated combustion scenarios.

Figure 11 illustrates the temperatures in the combustion chamber on a cut plane through the injector throughout the combustion simulation for the reference case and the case with early ammonia and late diesel pilot injection.

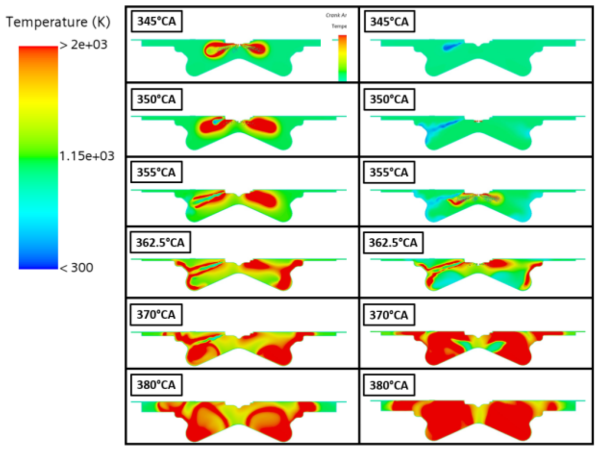


Figure 11. Ammonia-diesel DF combustion visualized by the temperature field on a cut plane through the combustion chamber, Comparison of Case 1 (left) and Case 2 (right)

In the reference case (Case 1), the diesel pilot ignites and combusts first. The ammonia spray then begins to penetrate the hot diesel combustion products. Ammonia burns as a diffusion flame after the flame transitions from diesel to ammonia combustion. When the ammonia spray hits the edge of the piston bowl, some of it is directed toward the cylinder head and some along the piston bowl toward the center of the cylinder. The burnout rate depends on the availability of oxygen. The backflow towards the center of the cylinder ensures additional mixing with oxygen, thus enabling complete ammonia combustion. In the case of early ammonia injection (Case 2), this backflow occurs earlier, and the ammonia has more time to premix with air. As soon as the late diesel pilot ignites the ammonia, the ammonia combusts very quickly.

Further validation cases use a reduced speed of 900 rpm at 75% load to approximate the in-cylinder conditions of a medium speed engine. Again, the combustion simulations are based on a successful charge exchange simulation. The three investigated combustion cases represent the same different combustion scenarios conducted with 1800rpm: almost simultaneous diesel and ammonia injection (Case 1), early ammonia and late diesel pilot injection (Case 2), and early diesel pilot injection (Case 3).

The following figures compare the simulated cylinder pressures with the experimental data (

Figure *12*) and show the simulated chemical HRRs during combustion (

Figure *13*):

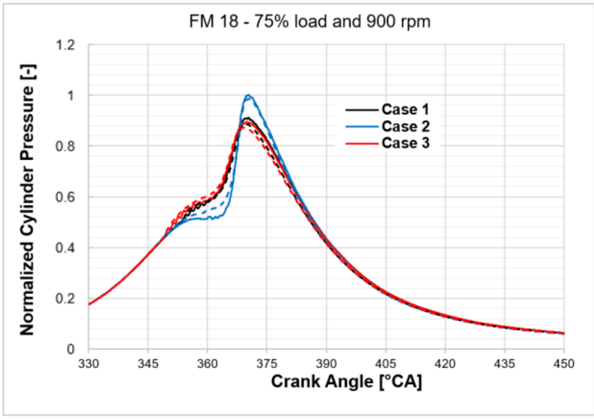


Figure 12. Normalized cylinder pressure of different combustion cases at 900 rpm and 75% load, comparison of simulations (solid lines) and experiments (dashed lines)

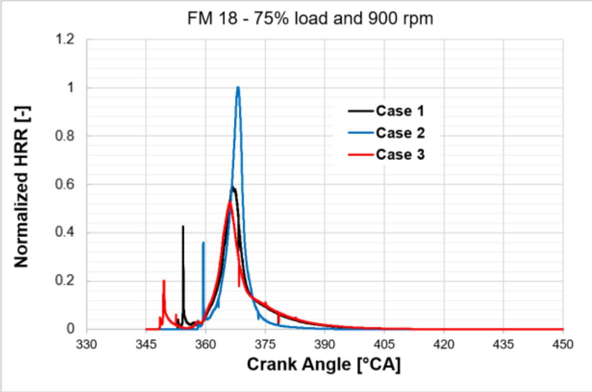


Figure 13. Normalized chemical HRRs predicted by the combustion simulations for different combustion cases at 900 rpm and 75% load

The predicted cylinder pressure is in good agreement with the experimental data for all three cases. The simulated heat release rates illustrate the different ammonia combustion behavior depending on the relative injection time. In the case of simultaneous or early diesel injection, undisturbed combustion of the diesel pilot occurs first. The hot diesel combustion products then ignite the injected ammonia in a slow transition to ammonia combustion. The maximum heat release rates are on a similar level in both cases. In the case of early ammonia injection with a late diesel pilot, the injected ammonia does not combust immediately but premixes partially. The partial premixing leads to rapid combustion and significantly higher maximum heat release rates as soon as the diesel pilot ignites the ammonia. The effects of the SOI variation on combustion behavior under medium speed conditions (900 rpm) are similar to those observed under high speed conditions (1800 rpm).

Another advantage of the complex chemistry approach is, that an evaluation of the pollutant formation during combustion is possible.

Table 2 gives a brief overview on the prediction accuracy of the complex chemistry simulations. The table shows the predicted pollutant formation normalized to the experimental data. It is possible to predict the correct order of magnitude for NO, NO2 and N2O pollutants. Even if the deviation for a single species can reach a factor of three, the prediction of total NOx + N2O is in excellent agreement with the experiment in case of early or simultaneous diesel injection. In case of very late diesel injection (Case 2) the prediction of total NOx + N2O is more challenging and deviates by a factor of two. For all cases the combustion simulations predict less ammonia slip. For medium speed conditions (900rpm) the difference is significant. Possible reasons may be the used chemical mechanism that leads to an overprediction of ammonia burnout or a changed quenching behavior for ammonia compared to conventional fuels.

Table 2. Predicted pollutant formation normalized to experimental data for high speed (1800 rpm) and medium speed (900 rpm) conditions

Species	Case 1 (1800 rpm)	Case 2 (1800 rpm)	Case 3 (1800 rpm)
NO	0.83	0.57	1.01
NO2	2.63	1.06	2.20
N2O	3.13	2.50	3.02
NOx + N2O	1.04	0.65	1.23
NH3	0.89	0.14	0.69
Species	**Case 1 (900 rpm)**	**Case 2 (900 rpm)**	**Case 3 (900 rpm)**
NO	1.08	1.97	0.88
NO2	1.57	0.90	2.22
N2O	2.44	2.46	1.88
NOx + N2O	1.11	1.93	0.91
NH3	0.00	0.04	0.01

In conclusion, the transfer of the simulation approach developed on base of the RCEM investigations was successful. By implementing a SOI variation, the validation of the combustion simulations at 1800 rpm and 75% load was achieved. The transferability of the simulation approach to medium speed boundary conditions was demonstrated by another SOI variation at 900 rpm and 75% load. Furthermore, the complex chemistry approach can predict pollutant formation in most cases in a satisfying way.

3.3 Combustion of ammonia in the test engine and the derived engine concept

This section presents a selection of results of the investigations in a 175 mm bore test engine. The results shown highlight the high potential of the HPDI combustion process and its high susceptibility to well-designed operating parameters. The engine investigations were conducted at the Wissenschaftlich Technisches Zentrum Rosslau (WTZ). Figure 14 shows the test engine's most important parameters.

The design of the nozzle and the spray orientation is derived from the findings of the RCEM tests described above. The injector used relies on a 3-1 needle concept and thereby features a central needle for diesel and three needles for ammonia surrounding the diesel needle. The diesel side is designed to inject small amounts of pilot diesel, but also high amounts of diesel to guarantee full load operation in Diesel model. Figure 15 illustrates the nozzle and the spray orientation of one of the test nozzles.

Single-cylinder research engine FM18

Parameter	Unit	Value
Bore	mm	175
Stroke	mm	215
Number of cylinders	-	1
Piston displacement	dm^3	5.17
Con rod length	mm	547
Rated power	kW	180
Rated speed	min^{-1}	1800
Number of valves	-	4
Compression ratio	-	19.2:1 (variable)
Camshaft	-	Axially tensioned (variable)

Figure 14. Data of the test engine [7]

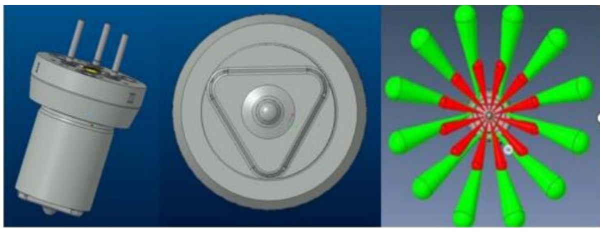


Figure 15. Nozzle and spray orientation of ammonia injector [6]

Different investigations were conducted on the test engine. The investigations include variations of injection timing, injection pressure, nozzle geometry, and the load point.

Figure *16*16 shows the engine behavior at an exemplary load point of 17 bar indicated mean effective pressure (IMEP) at an engine speed of 900rpm representative for medium speed engines. Two extreme cases are illustrated to show the effects of adapting injection parameters, i.e. injection timing and pressure. The different ammonia to NOx ratios (ANR) in the exhaust gas show that the combustion and emission behaviors can be influenced significantly by changing injection parameters. It is necessary to keep the ANR below 1 to avoid ammonia slip after the SCR catalyst, a requirement that can be fulfilled by carefully designing the engine and operating parameters as shown in these cases as well.

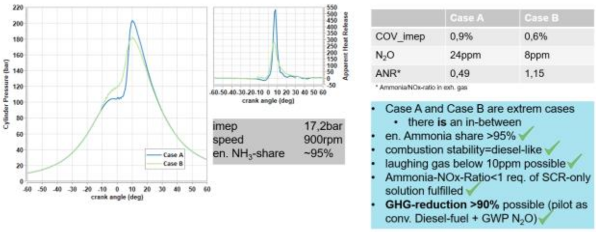


Figure 16. Two representative test engine operating points showing significantly different engine behavior. [8]

In both cases, the energetic ignition diesel pilot share is approx. 5%. Case B is characterized by slower combustion in comparison to case A and very low laughing gas (N_2O) emissions of 8ppm. The combustion stability (COV_imep) is high and comparable to diesel engines. For this case, however, the ammonia-NOx ratio (ANR) is slightly above 1 and is therefore insufficient for complete NH_3 conversion in the SCR catalyst. Case A is characterized by faster combustion. Combustion stability is slightly worse than in case B but is still sufficiently good. The condition required for complete ammonia conversion in the SCR catalyst (NOx>NH3) is reliably met with an ANR of 0,49. The laughing gas emissions remain at a low level, but increase compared to Case B. Showcasing the strong impact on changing operating conditions, the optimum parameters for operating the engine are between the two highlighted extremes.

In summary, when considering fossil diesel as pilot fuel and a carbon dioxide equivalence of 298 for laughing gas emissions, the total **GHG-emissions are reduced by more than 90% compared to pure diesel operation.**

Furthermore, these results show that NOx-emissions before the SCR catalyst and exhaust gas temperatures are similar to Diesel engines. Thus, the ammonia HPDI concept for a medium speed engine can meet the IMO T3 NOx limits by only requiring an SCR system as exhaust gas aftertreatment.

However, before switching to ammonia operation, the SCR catalyst must be warmed up to operating temperature. This is due to the fact that ammonia combustion always has a certain ammonia slip, which must be converted in the SCR catalyst. One option to increase the SCR system's temperature to operating conditions is heating it up by starting the engine in pure Diesel mode. The injector concept used in this study fulfills this requirement and avoids excessive ammonia emissions during the engine's start-up.

Thus, some minor changes on the SCR system may be necessary. As ammonia slip reduces the urea mass required for NOx-conversion in the SCR catalyst, the urea dosing system and control system may need adaptions for supplying the reduced urea amounts. The urea dosing must be capable to cover the full engine map for pure Diesel operation and operation with ammonia.

3.4 Safety measures for ammonia powered ships

As ammonia is highly toxic, ammonia engines require dedicated safety measures. Consequently, safety measures for bunkering, installation of ammonia tanks, and fuel systems will influence the ship's design significantly. Thus, making it challenging but possible to retrofit existing ships to ammonia. Concerning the engine itself, measures like double walled fuel piping and flushing systems are established technologies for LNG engines, which will have to be adapted and developed for the implementation of ammonia. Pressurizing ammonia up to several hundred bars with special off-engine ammonia pumps and the high-pressure piping to the injectors require special double wall compensators or, alternatively, on-engine high pressure pumps. For 4-stroke engines off-engine high pressure pumps are available, whereas compensators or on-engine high pressure pumps need to be developed. Special trainings for the crew, mechanics and machine operators are mandatory. Automation systems will play a decisive role to avoid human errors in ammonia operation or in the handling of ammonia. One such system, the capsulated ammonia fuel module (CAPSAM) concept was developed in the project AmmoniaMot by Neptun Ship Design (NSD). While safety onboard ammonia powered vessels remains challenging, increasing experience and technical solutions are increasingly facilitating its use. Because of these challenges and the resulting costs for safety measures, ammonia fueled engines are expected to enter operation on ammonia carriers first, before being used on vessels with a low number of crew members like container ships. Afterwards, we expect ammonia to further increase its market share in maritime applications, mainly via new-built ships. Due to green corridor concepts the investments in a bunkering infrastructure for the above mentioned first applications seem on a realistic level.

4 CONCLUSIONS AND OUTLOOK

MAN Energy Solutions SE has set out to decarbonize the engine portfolio with the introduction of new engine types that operate on hydrogen, methanol and ammonia. Simultaneously, retrofit kits are developed to upgrade selected legacy engines for using low-carbon, carbon neutral, and carbon free fuels to reduce the GHG emission of the existing fleet.

In this context, ammonia is highly promising as a fuel, due to its low prospective cost, an already high maturity of fuel production processes, easy storage and transport, as well as high availability. The blue version of ammonia may build the bridge required until sufficient green energy to produce green ammonia is available and may push the willingness to invest in ammonia production.

The fundamental investigations of ammonia combustion for 4-stroke engines presented in this work show that ammonia is a suitable fuel for 4-stroke engine applications. The diffusive ammonia combustion process investigated in this work is a suitable choice. The investigated concept demonstrates a GHG emission reduction of over 90%. The laughing gas emissions are on a very low level, while NOx-emissions and exhaust gas temperatures will meet IMO Tier 3 limits with common SCR systems.

The experiments conducted on the RCEM at the Technical University of Munich show that spray orientation, and thus nozzle design, have to be selected carefully. The investigations improved the understanding of ammonia combustion and provided guidelines for designing the nozzles used in the test engine. In addition, optical investigations on the RCEM helped setting up and validating a 3D CFD combustion model. This model proved its capability to predict combustion in the test engine. The model will accelerate the development of future ammonia engines and thus reduces development costs significantly.

Safety measures for the operation with ammonia are challenging, but solvable. As ammonia is highly toxic, safety measures for bunkering, installation of ammonia tanks and fuel systems will have a significant influence on the ship design. As a consequence, retrofitting ships to ammonia will be challenging but possible. Thus, ammonia will mainly be one of the future fuels for new-built ships. The complex challenge of choosing the economically most efficient propulsion and power generation setup depends strongly on the specific application. Therefore, we expect a diverse landscape of future fuels including green methanol and methane, as well as carbon free fuels like hydrogen and ammonia.

Due to the mentioned advantages as fuel, ammonia may also play a significant role in future power applications.

MAN Energy Solutions SE started the project AmmoniaMot 2 with partners from industry and research institutes to further explore the promising potential of ammonia-powered 4-stroke engines. The project aims to develop a 4-stroke, medium speed, dual-fuel test engine that runs on ammonia.

5 DEFINITIONS, ACRONYMS, ABBREVIATIONS

3D	three dimensional
AFR	Air Fuel Ratio
ANR	Ammonia-NOx-Ratio
bTDC	before Top Dead Center
CAPSAM	Capsulated Ammonia Module
CFD	Computional Fluid Dynamics
CH_4	methane
CN	Cetane Number
CO_2	Carbon Dioxide
COV_imep	co-variance of indicated mean effective pressure
DF	Dual-Fuel
DNV	Det Norske Veritas
ECFM-CLEH	Extended Coherent Flame Model – Combustion Limited by Equilibrium Enthalpy
e-fuels	fuels produced on base of green electricity
FtD	Fischer Tropsch to Diesel
FtK	Fischer Tropsch to Kerosene
GHG	Green House Gas
H_2	hydrogen
HPDI	High Pressure Direct Injection
HRR	Heat Release Rate
IMEP	Indicated Mean Effective Pressure
IMO	International Maritime Organization
LNG	Liquefied Natural Gas
LPDI	Low Pressure Direct Injection
MtG	Methanol to Gasoline
MtK	Methanol to Kerosene
N2O	nitrous oxide

NH_3	ammonia
NO	nitric oxide
NO2	nitrogen dioxide
NSD	Neptun Ship Design GmbH
OMEx	oxymethylenether
PFI	Port Fuel Injection
RCEM	Rapid Compression & Expansion Machine
SCR	Selective Catalytic Reduction
SOI	Start of Injection
TDC	Top Dead Center
TUM	Technical University of Munich
WLO	Woodward L'Orange
WTZ	Wissenschaftlich Technisches Zentrum Rosslau

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