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Technical indicators of ammonia heavy duty engines

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This article presents a literature review of the use of ammonia in combination with diesel fuel to power heavy duty engines. The main advantages and disadvantages in using ammonia as a fuel are shown. The chemical and physical properties of ammonia as a fuel compared to hydrogen are listed. Examples of the use of this type of engine by road, rail and marine transport companies were found. The effect of the energy content of ammonia in dual fuel on engine performance and emissions was determined.

1. Introduction

The needs of a rapidly changing automotive industry are forcing the development of new technologies in the design of road and rail vehicles. One of the main reasons for the introduction of new solutions is the climate crisis caused, among other things, by toxic and harmful emissions from internal combustion engines, mainly carbon dioxide. Globalisation has meant that more goods are transported than before. According to the data, the total gross weight of goods handled by EU ports was estimated at 3.4 billion tonnes in 2023 [9]. Ships, combustion locomotives and lorries are mainly equipped with heavy duty engines. According to statistics, transport is responsible for 17% of carbon dioxide emissions into the atmosphere [19]. One solution for decarbonising engines is to use carbon-free fuels such as ammonia and hydrogen. Taking both facts into account, it can be concluded that the use of zero-carbon fuels in heavy duty engines can contribute significantly to reducing the impact of the transport sector on the climate crisis.

The advantage of hydrogen as a fuel is its ubiquity on Earth. For this reason, the hydrogen on the market can be divided into the following types, which differ in terms of how it is produced [20] (Fig. 1):

- Green hydrogen – produced by electrolysis of water and reforming of biogas
- Red hydrogen – produced by electrolysis of water, using electricity from a nuclear power station
- Grey hydrogen – produced by reforming natural gas and other petroleum hydrocarbons
- Blue hydrogen – produced from fossil fuels using carbon dioxide capture technology
- White hydrogen – derived from natural geological sources
- Black hydrogen – produced by coal gasification
- Yellow hydrogen – produced by electrolysis of water using electricity from solar panels
- Brown hydrogen – produced by the gasification of brown coal
- Turquoise hydrogen – produced by pyrolysis of methane.

One of the challenges of using hydrogen as a fuel is how efficiently it can be sourced through environmentally friendly means. The most economical method of hydrogen production is steam-methane reforming. In the process, steam and methane react to form carbon monoxide and hydrogen as by-products. Other

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major hydrogen production processes include partial petroleum oxidation, petroleum cracking, coal gasification and coal cracking. Hydrogen produced from coal sources currently accounts for 30% of production and hydrogen from petroleum accounts for 18% of production [23].

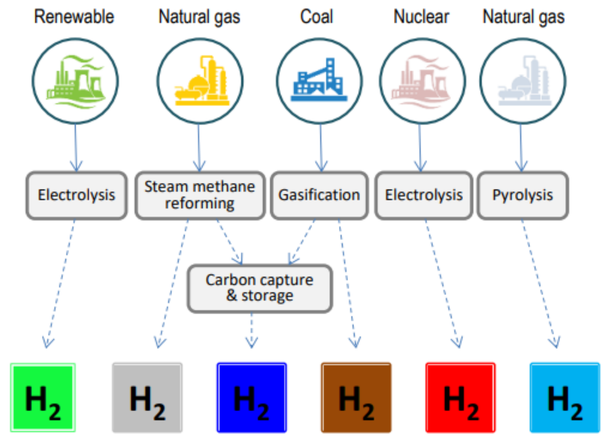

Fig. 1. Methods of hydrogen production and the associated “colors” of hydrogen made [20]

The second carbon-free fuel considered is ammonia. The advantage of ammonia as a fuel is that procedures for the safe handling of large quantities of it are well-established and documented. The infrastructure for its transport by rail, road or pipeline exists in many countries. Ammonia production was developed about 100 years ago by Haber and Bosch. The method, known mainly as the Haber-Bosch process, uses an iron-based catalyst, high pressure (100–300 atm.) and increased temperature (400–500°C) to synthesize hydrogen with nitrogen. Large-scale industrial production of ammonia was initiated in 1913 at the BASF company. The main use of ammonia is the production of fertilizers used in agriculture. This has contributed to a significant increase in food productivity, making it possible to meet the needs of a rapidly growing world population. Ammonia is also used as a production raw material in many industrial products and as a coolant in large refrigeration systems [13]. Ammonia is an efficient hydrogen carrier. In general, it offers a higher hydrogen density than liquid hydrogen per unit volume, making it a more viable alternative to conventional fuels [6].

Both of the above-mentioned alternative fuels could find wider application in the transport industry. Besides using them separately, there is also the concept of using them together. The main advantage of hydrogen is the low energy needed to ignite it and the high speed of flame propagation. The disadvantages of hydrogen include the difficulty of its storage. Ammonia is an alternative fuel that is easier to store, but its flammability range is narrow. By using both fuels simultaneously, in a two-stage combustion system, it is possible to achieve a fuel that is easier to store and has a wide flammability range. Research has already been undertaken in this area [14, 21, 31].

2. Properties of hydrogen as a fuel

Hydrogen is the most common element on Earth. The small and light hydrogen molecule is very mobile (high mass diffusivity) and leads to a very low density under atmospheric conditions. Hydrogen as a fuel has a wide flammability range falling within the excess air ratio (λ) range of 0.14 to 10. Practically, the limit of a lean hydrogen-air mixture is reached for lower values of the excess air ratio than mentioned above, namely for $\lambda = 4$. The calorific value of hydrogen is 120 MJ/kg. The advantage of a hydrogen-air mixture is the low minimum energy required to ignite it. Under atmospheric conditions, it is only 0.017 mJ for $\lambda = = 1.2–1.5$. This value is an order of magnitude less than the energy required to ignite an iso-octane or methane air mixture. An important aspect of determining the safe use of all fuels is their self-ignition temperature. Hydrogen has an self-ignition limit located in the temperature range from about 773 K (500°C) to about 858 K (585°C) [25]. However the disadvantage of hydrogen relative to petrol is that it has a lower volumetric energy density, making it need about 4 times more volume to store the same energy. It is worth noting that the flame propagation velocity during the combustion of a hydrogen-air mixture is an order of magnitude higher than the flame propagation velocity resulting from the combustion of petrol with air. Hydrogen has a high diffusivity in air, which helps to create a homogeneous fuel-air mixture. The ease with which hydrogen disperses in the air also means that if the fuel leaks from the tank into the atmosphere, the risk of dangerous events such as explosions is reduced [22].

3. Properties of ammonia as a fuel

The ammonia molecule has the shape of a trigonal pyramid with three hydrogen atoms and an unshared pair of electrons attached to a nitrogen atom. Ammonia is an alkaline, colourless gas with a strong smell. The boiling point of ammonia is 240 K, while the freezing point is 195.5 K. Under atmospheric conditions, the self-ignition temperature of ammonia is 924 K, which is higher than the self-ignition temperature of hydrogen, this affects the safety of storage. Ammonia can be easily liquefied and stored at a relatively low pressure of 1030 kPa at ambient temperature. It is also possible to store it at a low temperature of 240 K at ambient pressure. Immediately life- or health- hazardous level of ammonia in the air is 300 ppm [8], however, in gaseous form it has a strong aroma detectable at much lower concentrations – from about 5 ppm [30]. The calorific value of ammonia compared to hydrogen is low and equals 18.6 MJ/kg [6]. It is worth noting that the energy density of liquid ammonia is 12.7 MJ/dm^3 and is significantly higher than the energy density of liquid hydrogen, which is 8.49 MJ/ dm^3 [4]. The maximum laminar combustion velocity of ammonia reaches 0.07 m/s, compared to hydrogen this is almost 42 times slower. The flammability range for ammonia is between 0.63 and 1.4 equivalence ratio, which converts to a range of about 0.7 to approximately 1.6 excess air ratio [6]. The energy required for the ignition of ammonia is 8 mJ, compared to hydrogen this is significantly higher value. The most important advantage of ammonia over hydrogen is that it is much easier to transport and store. Ammonia can be a gas under atmospheric conditions, but is usually transported in the liquid state by pipelines, tank trucks and tankers. For tankers, the ammonia is usually cooled to –33^{o}C, allowing low-pressure tanks to be used. Two methods are mainly used to store ammonia in the liquid state. The first is to increase the pressure while maintaining the ambient temperature. The second method involves lowering the temperature while maintaining atmospheric pressure. The second method allows the use of lighter and cheaper tanks. The infrastructure for storing and transporting propane can also be used for liquid ammonia, therefore using it as a carbon-free fuel can become economically efficient [4]. Table 1 shows the properties of hydrogen and ammonia to highlight the differences between them.

Table 1. Comparison of the properties of hydrogen and ammonia as fuels [4, 6, 8]

Parameter	Hydrogen	Ammonia
Flammability range (excess air ratio)	0.14–10	0.7–1.6
Calorific value [MJ/kg]	120	18.6
Energy required for ignition [mJ]	0.017	8
Self-ignition temperature [K]	773–858	924
Maximum laminar combustion velocity [m/s]	2.91	0.07

In summary, ammonia has inferior properties to hydrogen as a fuel, but the way it is produced, stored and transported means that its use can be more economically efficient.

4. Possibilities of using ammonia in HD engines

Ammonia is the inorganic chemical compound of nitrogen and hydrogen (NH_3). The chemical composition of ammonia means that its combustion in an engine results in relatively high emissions of nitrogen oxides. This leads to the need for suitable catalytic exhaust after-treatment systems, which require space. This makes ammonia suitable for use in heavy duty, marine or power generations [8].

Currently, the majority of heavy duty engines used in the transport sector are diesel engines. This is due to the greater efficiency of these engines relative to engines that run on petrol [7]. As a result of fuel combustion, diesel engines emit toxic compounds such as carbon monoxide, nitrogen oxides, hydrocarbons, particulate matter. Diesel engines also emit carbon dioxide, which is a greenhouse gas [32]. Ammonia itself, due to its previously mentioned poor combustion properties, is not suitable as a fuel for heavy duty engines of lorries. Research shows that in order to successfully ignite ammonia alone in a diesel engine, it would need to operate with a compression ratio of between 35:1 and 100:1, which is a very high value [8]. Current heavy duty diesel engines operate with compression ratio ranging from 16:1 to 23:1. For this reason, the line of research being developed seeks to use a dual fuel, ammonia with the addition of diesel. According to research, the use of such a fuel made it possible to achieve self-ignition of the mixture for a compression ratio of 15.2:1. The use of pure ammonia as a fuel is currently mainly developed by the shipping industry. This is due to the use of marine large bore diesel engines [24].

5. Examples of the use of ammonia in propulsion systems

An example of the use of ammonia in heavy duty engines is a project carried out by Hyundai Heavy Industries (HD HHI). The company has developed an ammonia engine that burns ammonia – diesel, a dual fuel (Fig. 2).

Fig. 2. The HiMSEN Ammonia Dual-Fuel Engine (model H22CDF-LA) developed by HD Hyundai Heavy Industries [11]

The engine generates between 1.4 and 2.2 MW and can be used for marine transport and power generation. It is a high-pressure direct-injection ammonia engine designed to minimise greenhouse gas emission. The engine controls the emissions of nitrogen oxides and unburned ammonia in the exhaust gas, effectively reducing them using only a selective catalytic reduction system. From 30 September to 2 October 2024, HD HHI carried out a successful type-approval test of the engine [11].

An interesting application of ammonia for heavy duty vehicle propulsion is the solution presented by company Amogy. The company in 2023 has developed a semi-truck equipped with a propulsion system that starts with ammonia and ends with electricity to power electric motors (Fig. 3). The first stage of the propulsion system is to break down the ammonia into hydrogen, then the hydrogen is supplied to the fuel cells, which generate electricity to be supplied to the engines that drive the semi-truck. The company is currently scaling up the technology it has developed so that it can be used to propel a vessel. In September 2024, the company made its first voyage on a vessel called Kraken, which is powered by ammonia. The tugboat was originally built in 1957 and has now been upgraded with Amogy's ammonia to electric power system [2, 3].

Fig. 3. Class 8 ammonia powered truck [2]

In 2020, the Danish investment company Innovation Fund Denmark announced the creation of a consortium to develop an ammonia-powered two-stroke engine for marine transport. The consortium was to be led by MAN Energy Solutions. The consortium was to include the following entities: Eltronic FuelTech, Technical University of Denmark, DNV GL. The location for the engine development was to be the MAN Energy Solutions research centre in Copenhagen. The project had the following objectives [17]:

- development of the concept and preliminary design of the ammonia engine
- development of an ammonia-based fuel supply system
- comprehensive engine test operation.

In July 2023, MAN Energy Solutions succeeded in burning ammonia in a two-stroke research engine. A small pilot flame was needed to start the combustion of ammonia. Initial tests were carried out with 10–15% of the pilot diesel dose. The R&D objective was to achieve ignition for a proportion of approximately 5% diesel at 100% load. The remaining 95% of the energy will be provided by ammonia. In December 2024, MAN Energy Solution announced the start of testing of a full-scale engine powered by ammonia ME-LGIA (Liquid Gas Injection Ammonia) – Fig. 4. The research will focus on performance, combustion and emissions, engine-tuning, atomizer testing and control-system verification. The full-scale two-stroke ammonia engine is based on the MAN B&W ME-LGI engine concept, which is a dual-fuel solution of methanol and diesel, or LPG and diesel. The prefix ME refers to the electronically controlled engine. ME-LGIA will be available as a new engine or as a retrofit option for existing electronically controlled engines [15, 16].

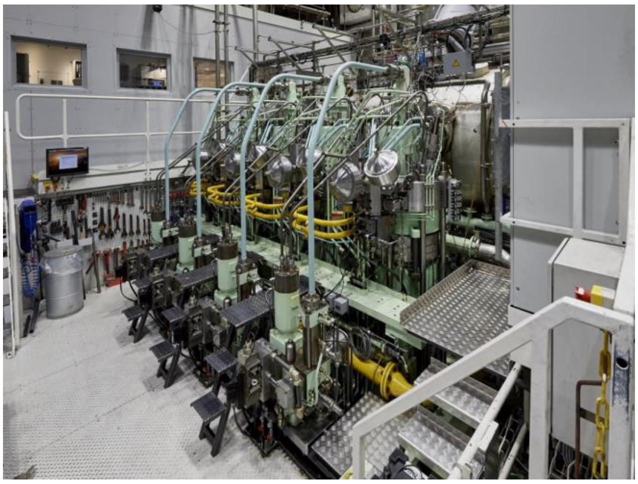

Fig. 4. The ME-LGIA research engine (4T50) at Research Centre Copenhagen [16]

Another example of the use of ammonia in a marine engine is the company Wärtsilä, which in 2023 started a project to develop the first marine four-stroke engine powered by this alternate fuel. The new engine will be based on a unit Wärtsilä 25 (Fig. 5). It is a medium-speed engine, capable of burning diesel alone or dual fuels. The engine will have a piston diameter of 250 mm and a piston stroke of 340 mm. The engine will run at 900/1000 rpm. The ammonia version of the Wärtsilä 25 will come in four versions differing in number of cylinders and volume, 6 dm^3, 7 dm^3, 8 dm^3 and 9 dm^3. Depending on the version, the engine will generate between 1.7 and 3.4 MW. One cylinder will generate 280 kW or 305 kW depending on the mode of operation. The engine is designed to power smaller commercial vessels, fishing boats, tugboats, dredgers, and offshore support vessels [26, 27].

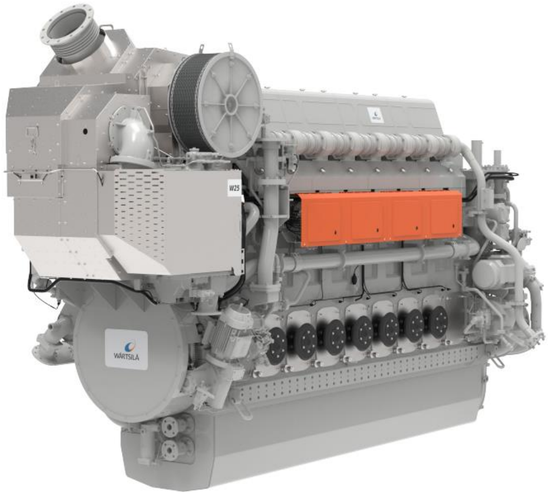

Fig. 5. Wärtsilä 25 four-stroke ammonia engine [26]

There is currently no example of an ammonia-powered passenger car, but in 2023, the Chinese company GAC automotive announced at the GAC Tech Day conference, work on such an engine. The concept presented is intended to allow ammonia ignition to be achieved without problems, thereby generating 120 kW (161 hp). Assumptions are that the engine will achieve a 90% reduction in carbon dioxide emission [10].

6. Performance indicators and emissions of heavy duty ammonia engines

For heavy duty engines, it is important to determine the effect of ammonia on performance compared to diesel, which is their conventional fuel. Such a study was conducted by Yousefi et al. [29]. The test involved checking the performance of a heavy duty compression ignition engine during an increase in the proportion of ammonia in a dual fuel. The research was carried out on a dynamometer with a single-cylinder research engine. A schematic of the test bench is shown in Fig. 6.

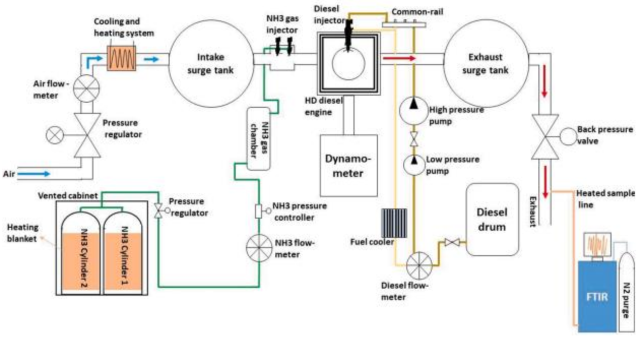

Fig. 6. Schematic diagram of engine test setup [29]

The basic parameters of the test engine are shown in Table 2. The test was carried out for a constant BMEP (brake mean effective pressure) and engine speed of 8.10 bar and 910 rpm, respectively. During the test, diesel fuel was injected directly into the combustion chamber and ammonia into the intake system.

Table 2. Engine specifications [29]

Parameter	Parameter description
Engine model	Caterpillar 3401
Number of cylinders	1
Bore × stroke [mm × mm]	137.2 × 165.1
Conrod length [mm]	261.62
Compression ratio	16.25:1
Displacement [dm^3]	2.44
Intake valve opening [°CA bTDC]	1.7
Intake valve closing [°CA aTDC]	190.3
Exhaust valve opening [°CA aTDC]	505.3
Exhaust valve closing [°CA aTDC]	708.3

In the test, the amount of ammonia was increased so that its share first corresponded to 20% of the energy contained in the dual fuel, then to 40% of the energy. During the first measurement run, diesel alone was supplied to the engine. During this test, the following parameters were verified: mean effective pressure, indicated thermal efficiency of the engine, heat release rate, peak pressure rise rate.

Figure 7 shows that the maximum pressure inside the combustion chamber decreases as the energy content of ammonia in the fuel increases. Analysing the heat release rate data, it can be observed that increasing the proportion of ammonia increases the first peak of this magnitude, while the second peak has an inverse relation.

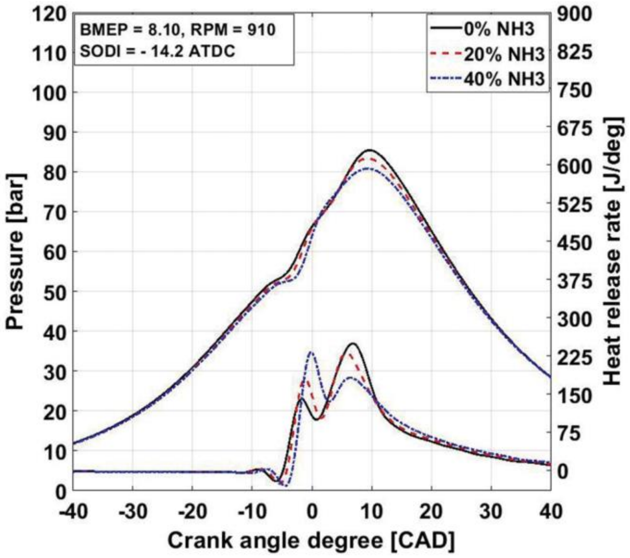

Fig. 7. Cylinder pressure and heat release rate [29]

Figure 8 shows that the cylinder pressure increased faster as the proportion of ammonia in the fuel increased. Both the increase in the first heat release rate peak and the peak pressure rise rate suggest that most of the diesel-ammonia-air mixture burns under pre-combustion conditions.

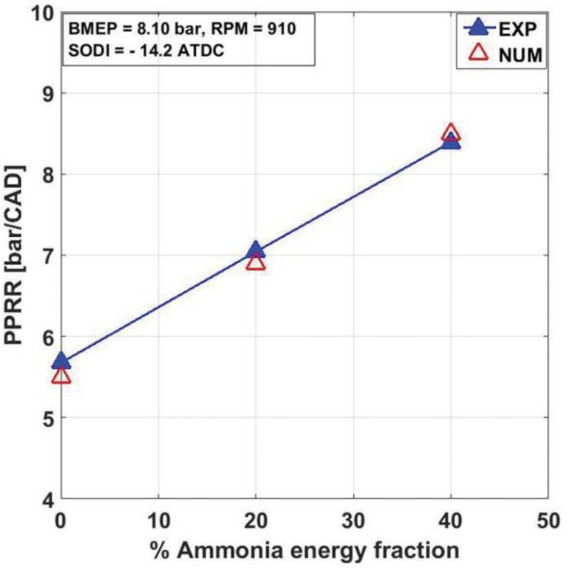

Fig. 8. Peak pressure rise rate [29]

The characteristic shown in Fig. 9 clearly shows that as the proportion of ammonia in the fuel increases, the thermal efficiency of the engine decreases. This decrease is mainly due to the lower flame propagation velocity and the difficulty in self-ignition of the air-fuel mixture [29].

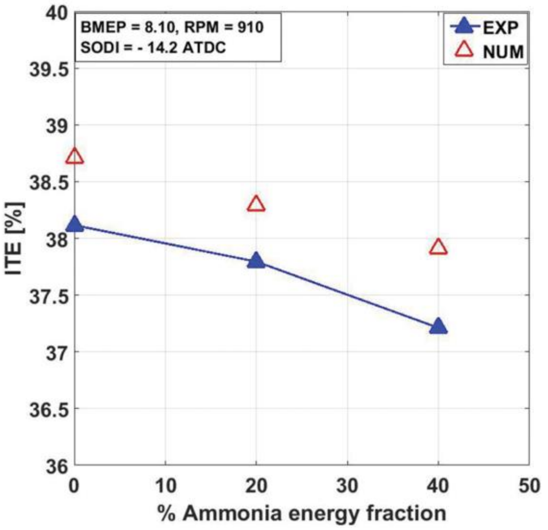

Fig. 9. Indicated thermal efficiency [29]

The main purpose of using ammonia in combination with diesel is to reduce greenhouse gas emissions. The effect of the energy share of ammonia in dual fuel on emissions of these gases and nitrogen oxides was investigated by Jin et al. [12]. The test was carried out on a test bench equipped with a six-cylinder engine, but all tests were carried out on the 6th cylinder, and cylinders 1 to 5 were fuelled only to ensure speed (Fig. 10).

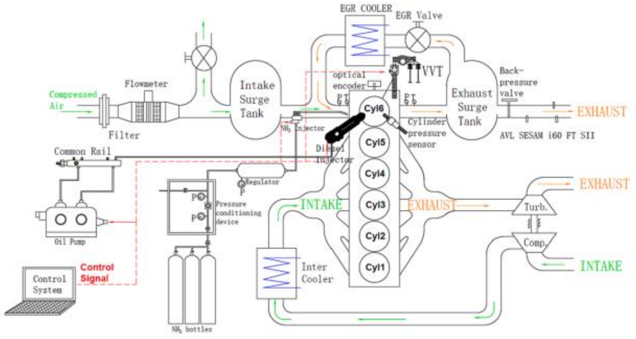

Fig. 10. Schematic of the experimental setup [12]

The technical parameters of the engine are shown in Table 3.

Table 3. Engine parameters [12]

Item	Value
Bore × stroke [mm × mm]	116 × 150
Compression ratio	18.5:1
Displacement [dm^3]	9.5
In cylinder peak pressure [MPa]	24
Ammonia injection method	Port injection
Ammonia injection pressure [bar]	6
Nozzle number × diameter [mm]	8 × 0.169

All experimental results were measured under steady-state conditions at a constant engine speed of 1000 rpm and an inlet pressure of 1.2 bar. Diesel injection pressure was 60 MPa and ammonia pressure after decompression was 6 bar.

Figure 11 shows the emissions of compounds resulting from improper combustion of the fuel-air mixture, namely CO, HC, NH_3. As the share of ammonia increases, CO decreases which is due to the lower share of diesel, which is a carbon-containing fuel. As the energy share of ammonia increases, the emissions of unburned HC and NH_3 increase, due to a lower laminar combustion speed and inefficient ignition of ammonia when the mass of diesel fuel is low.

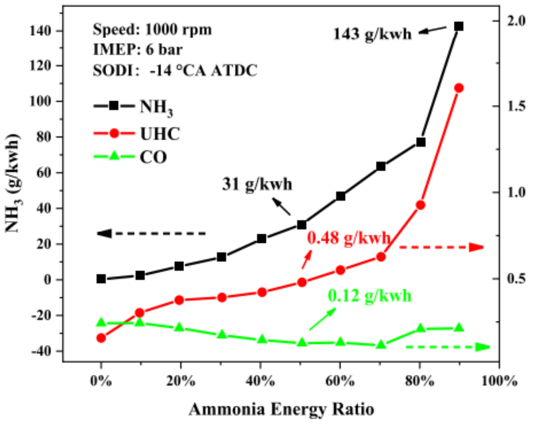

Fig. 11. Incomplete combustion emissions [12]

Figure 12 shows NO, NO_2 and N_2O emissions depending on the proportion of ammonia in the fuel. It can be observed that both NO and NO_2 emissions decreased as the energy share of ammonia increased. This is explained by the lower combustion temperature. Nitrogen under atmospheric conditions does not react with oxygen, but under conditions of high pressure and high temperature it does. Figure 13 shows that the combustion temperature decreased as the proportion of ammonia in the fuel increased, resulting in lower emissions of NO and NO_2.

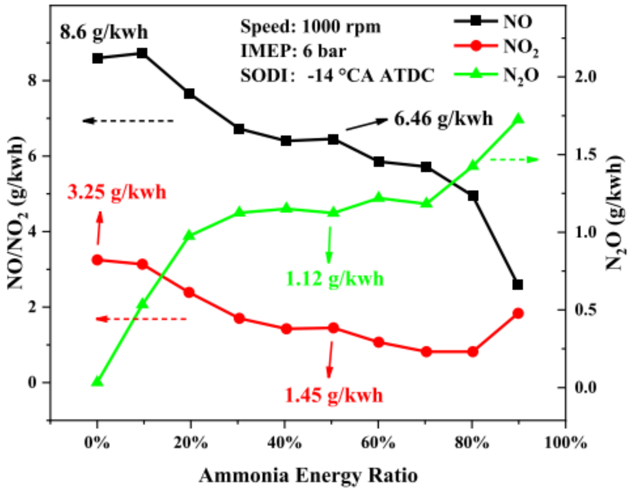

Fig. 12. NO_x emissions [12]

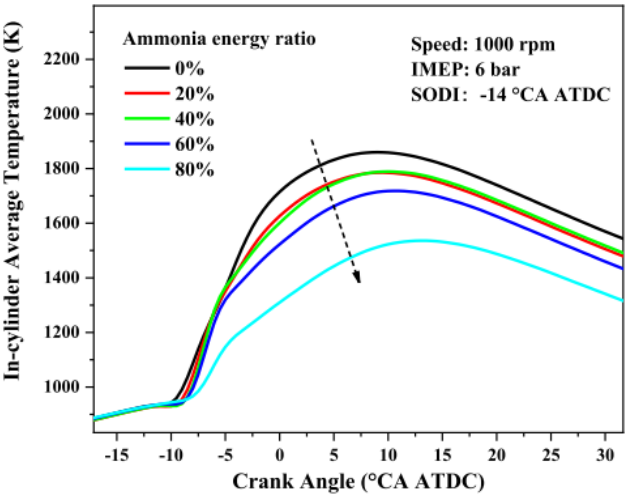

Fig. 13. In-cylinder average temperature [12]

A negative aspect observed is the increasing of N_2O emissions as the energy share of ammonia in the fuel grows. is also a greenhouse gas, so it cannot be ignored in further consideration of the use of ammonia-fueled engines.

Figure 14 shows the dependence of greenhouse gas emissions and CO_2 itself on the energy share of ammonia in the fuel. It can be observed that CO_2 emissions are decreasing which is due to the lower mass of diesel in the fuel. However, greenhouse gas emissions themselves are increasing due to the surge in N_2O, which is contrary to the purpose of using ammonia as a fuel. However, it is worth noting that N_2O, as an intermediate product of nitrogen, is easily decomposed at high temperatures, which provides an opportunity to reduce emissions of this compound [12].

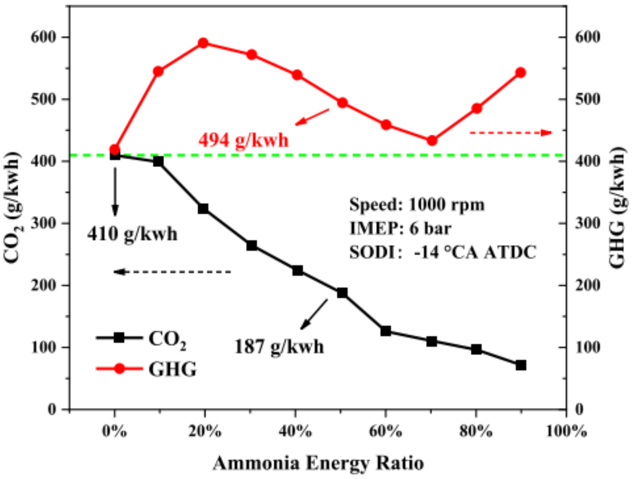

Fig. 14. CO_2 and GHG emissions [12]

Solving the problem of excessive greenhouse gas emissions by using ammonia and overlooking the fact of increased N_2O emissions is a mistake. Therefore, the key in the use of heavy duty engines fueled with this alternative fuel is to find the right strategy to supply these engines in terms of reducing emissions of unburned NH_3 and N_2O. Such research was undertaken by Mi et al. [18]. The test involved checking the emissions of an engine fueled by ammonia and diesel as a function of the size of the pilot diesel fuel injection rate. Ammonia was injected into the engine's intake system during the test, while diesel was injected directly into the combustion chamber. Diesel injection was divided into main and pilot dose. Injection of the main dose started at 20°CA bTDC, while injection of the pilot dose 60°CA bTDC. During the study, the percentage of the pilot dose relative to the main dose was increased. The percentage share of ammonia energy in the dual fuel during the test was 50%. The tests were carried out on a four-cylinder diesel engine, but three cylinders of the engine operated at constant speeds and loads, while the fourth cylinder with independent fuel injection, intake and exhaust systems worked as a test cylinder (Fig. 15).

The basic technical parameters of the engine are shown in Table 4.

Figure 16 shows that unburned ammonia emissions decrease significantly when increasing the energy share of the pilot dose.

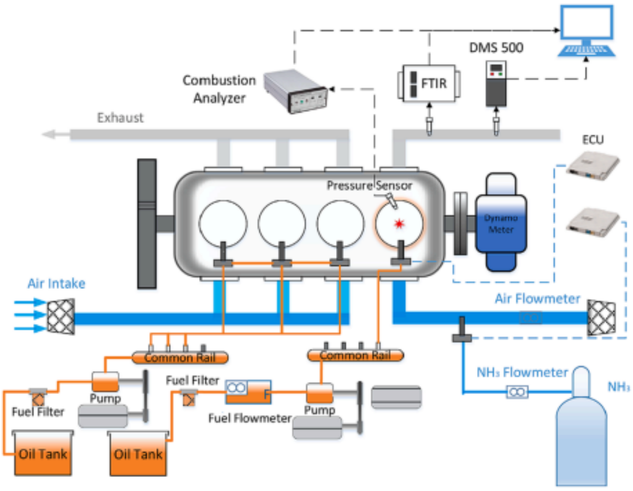

Fig. 15. The schematic of the experimental setup [18]

Table 4. Engine specifications [18]

Parameters	Value
Bore [mm]	114
Stroke [mm]	130
Connection rod length [mm]	216
Compression ratio [-]	18:1
Intake valve opening [°CA bTDC]	22
Intake valve closing [°CA aTDC]	246
Exhaust valve opening [°CA aTDC]	472
Exhaust valve closing [°CA aTDC]	694

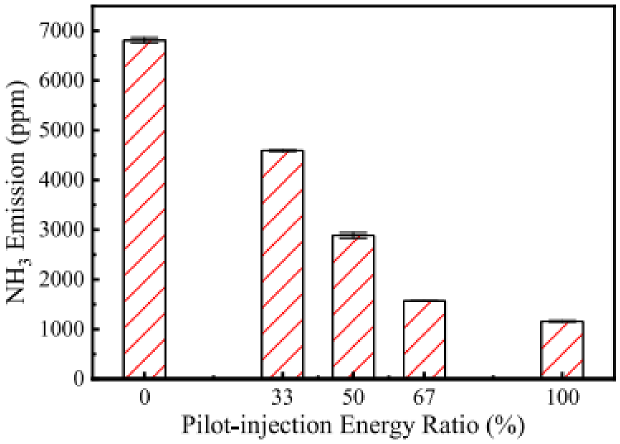

Fig. 16. Effect of diesel pilot-injection energy ratio on NH_3 emission [18]

Figure 17 shows the effect of pilot dose size on N_2O emission. Increasing the energy share of the diesel pilot dose has the potential to reduce emissions of this greenhouse gas.

The above study showed that it is possible to significantly reduce emissions of unburned NH_3 and N_2O by properly controlling engine operation. Combining these strategies with appropriate exhaust aftertreatment systems is the key to using ammonia as a fuel for heavy duty engines. However, a study by Cano Blanco et al. [5], showed that although commercial technologies are available to reduce N_2O and NO_x emissions, their direct application to newly developed ammonia engines is not straightforward, mainly due to the unique operating conditions of these engines. Achieving N_2O conversion at low temperatures (around 350°C) in the presence of a full exhaust gas mixture including NO_x, N_2O, NH_3, oxygen, and water is a challenge. This difficulty is compounded by the inhibitory effects of water, oxygen, and the need for optimal dosage of NH_3, which are becoming key factors [5].

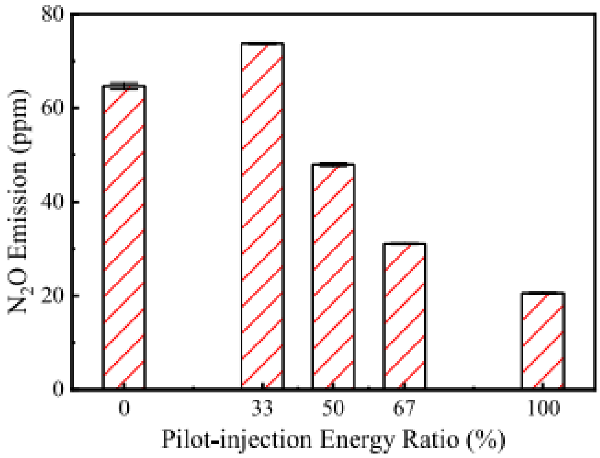

Fig. 17. Effect of diesel pilot-injection energy ratio on N_2O emission [18]

7. Challenges

When considering the use of ammonia in heavy duty engines, it is important to take into account the corrosive nature of this compound and the fact that it can adversely affect the lubricating film of the engine oil. Both aspects impact on the reliability and lifetime of the engine.

The behaviour of metals in an ammonia environment can vary significantly depending on factors such as ammonia concentration, temperature and exposure time. Studies show that high concentrations of ammonia can accelerate corrosion, especially in the case of copper and aluminium, while steel is relatively more resistant to corrosion. The main type of damage to steel in an ammonia environment is stress corrosion cracking. However, this phenomenon can be reduced by adding a small amount of water (0.1–0.5 wt.%) to the ammonia fuel. However, it is important to remember that ammonia easily combines with water to form an ammonia solution, which can also corrode metals. Moreover, water can enter the system in various ways, including as a component of the fuel itself. According to a study by Xu et al. [28] the ammonia solution can improve the thermal and dispersion stability of lubricating oil, and bind additive components, which can weaken the anti-wear properties of the oil [1]. Research into lubricating oils for ammonia-fuelled engines is in an early stage. The effect of ammonia fuel and its combustion products on lubricating oil performance remains unclear, although there are papers exploring ways of testing oil for such engines [28]. These studies will show if current lubricating oils are able to meet the requirements of ammonia-fuelled engines, and whether their composition needs to be modified.

8. Conclusions

The research presented above shows that the performance of an engine burning ammonia-diesel dual fuel is inferior compared to the combustion of pure diesel fuel. This is caused, among other things, by the low laminar propagation of the flame and the high ignition temperature of ammonia. A positive aspect of burning ammonia fuel is lower carbon dioxide emission. The main disadvantage of heavy duty engines fuelled with ammonia fuels is higher emissions of unburned NH_3 and N_2O, which is also a greenhouse gas. However, studies show that by choosing the right strategy for supplying an ammonia engines and using exhaust aftertreatment systems, it is possible to reduce the negative environmental impact of this engines. To make this happen, the exhaust aftertreatment systems must be properly adapted to the new engines, which may be difficult. Besides the emission of ammonia engines, it is also a challenge to reduce the negative effects of ammonia on engine parts corrosion and lubrication, but the fact that the above mentioned companies are currently working on such engines suggests that this is possible.

Nomenclature

aTDC	after top dead centre	ITE	indicated thermal efficiency
bTDC	before top dead centre	LGIA	liquid gas injection ammonia
BMEP	brake mean effective pressure	LPG	liquefied petroleum gas
CI	compression ignition	NH_3	ammonia
CO	carbon monoxide	NO	nitrogen oxide
CO_2	carbon dioxide	PPRR	peak pressure rise rate
DI	direct injection	SI	spark ignition
ECU	electronic control unit	SODI	start of diesel injection
EGR	exhaust gas recirculation	UHC	unburned hydrocarbons
GHG	greenhouse gases	VVT	variable valve timing
HD	heavy duty	λ	excess air ratio
HD HHI	Hyundai Heavy Industries		

Bibliography

[1] Agocs A, Rappo M, Obrecht N, Schneidhofer C, Frauscher M, Besser C. The impact of ammonia fuel on marine engine lubrication: an artificial lubricant ageing approach. Lubricants. 2023;11(4):165. https://doi.org/10.3390/lubricants11040165

[2] Amogy. Amogy presents world's first ammonia-powered, zero-emission semi truck. https://amogy.co/amogy-presents-worlds-first-ammonia-powered-zero-emission-semi-truck/?utm_source=chatgpt.com (accessed on 29.12.2024).

[3] Amogy. Amogy sails world's first carbon-free ammonia powered maritime vessel. https://amogy.co/amogy-sails-worlds-first-carbon-free-ammonia-powered-maritime-vessel/ (accessed on 29.12.2024).

[4] Aziz M, Wijayanta AT, Nandiyanto ABD. Ammonia as effective hydrogen storage: a review on production, storage and utilization. Energies. 2020;13(12):3062. https://doi.org/10.3390/en13123062

[5] Cano Blanco D, Elsener M, D'Alessandri J, Peitz D, Ferri D, Kröcher O. Critical aspects in the catalytic emission control of exhaust gases containing NH_3, NO_x and N_2O. Journal of Ammonia Energy. 2024;2: 674-72. https://doi.org/10.18573/jae.32

[6] Chai WS, Bao Y, Jin P, Tang G, Zhou L. A review on ammonia, ammonia-hydrogen and ammonia-methane fuels. Renew Sust Energ Rev. 2021;147:111254. https://doi.org/10.1016/j.rser.2021.111254

[7] Cunanan C, Tran MK, Lee Y, Kwok S, Leung V, Fowler M. A review of heavy-duty vehicle powertrain technologies: diesel engine vehicles, battery electric vehicles, and hydrogen fuel cell electric vehicles. Clean Technol. 2021;3(2):474-489. https://doi.org/10.3390/cleantechnol3020028

[8] Dimitriou P, Javaid R. A review of ammonia as a compression ignition engine fuel. Int J Hydrogen Energ. 2020;45(11):7098-7118. https://doi.org/10.1016/j.ijhydene.2019.12.209

[9] Eurostat. Maritime transport of goods – annual data. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Maritime_transport_of_goods_-_annual_data (accessed on 29.12.2024).

[10] GAC International. GAC unveils industry-first innovations at GAC TECH DAY 2023. https://www.gac-motor.com/en/media/newsdetail/id/296.html (accessed on 29.12.2024).

[11] Hyundai Heavy Industries | Engine & Machinery. HD Hyundai Heavy Industries develops ammonia dual-fuel engine and receives approval from 7 major classification societies. https://www.hyundai-engine.com/en/media/newsdetail/435 (accessed on 29.12.2024).

[12] Jin S, Wu B, Zi Z, Yang P, Shi T, Zhang J. Effects of fuel injection strategy and ammonia energy ratio on combustion and emissions of ammonia-diesel dual-fuel engine. Fuel. 2023;341:127668. https://doi.org/10.1016/j.fuel.2023.127668

[13] Kobayashi H, Hayakawa A, Kunkuma KD., Somarathen A, Okafor EC. Science and technology of ammonia combustion. P Combust Inst. 2019;37(1): 109-133. https://doi.org/10.1016/j.proci.2018.09.029

[14] Liu Z, Wei H, Shu G, Zhou L. Ammonia-hydrogen engine with reactivity-controlled turbulent jet ignition (RCTJI). Fuel. 2023;348:128580. https://doi.org/10.1016/j.fuel.2023.128580

[15] MAN Energy Solutions. A new chapter – ammonia two-stroke engines. https://www.man-es.com/marine/products/two-stroke-engines/ammonia-engine?592380e5-7b22-42aa-bf83-f8dd18223552%5B%5D=2 (accessed on 29.12.2024).

[16] MAN Energy Solutions. Full-scale ammonia engine opens new chapter. https://www.man-es.com/company/press-releases/press-details/2024/12/03/full-scale-ammonia-engine-opens-new-chapter (accessed on 29.12.2024).

[17] MAN Energy Solutions. MAN Energy Solutions leitet dänisches Konsortium zur Entwicklung eines mit Ammoniak betriebenen Motors für die Schifffahrt. https://www.man-es.com/de/unternehmen/pressemitteilungen/press-details/2020/10/21/man-energy-solutions-leitet-daenisches-konsortium-zur-entwicklung-eines-mit-ammoniak-betriebenen-motors-fuer-die-schifffahrt (accessed on 29.12.2024).

[18] Mi S, Wu H, Pei X, Liu C, Zheng L, Zhao W et al. Potential of ammonia energy fraction and diesel pilot-injection strategy on improving combustion and emission performance in an ammonia-diesel dual fuel engine. Fuel. 2023;343:127889. https://doi.org/10.1016/j.fuel.2023.127889

[19] Onorati A, Payri R, Vaglieco B, Agarwal A, Bae C, Bruneaux G et al. The role of hydrogen for future internal combustion engines. Int J Engine Res. 2022; 23(4):529-540. https://doi.org/10.1177/14680874221081947

[20] Pielecha I, Engelmann D, Czerwinski J, Merkisz J. Use of hydrogen fuel in drive systems of rail vehicles. Rail Vehicles/Pojazdy Szynowe. 2022;1-2,10-19. https://doi.org/10.53502/RAIL-147725

[21] Pielecha I, Szwajca F. Combustion characteristics of a hydrogen-fueled TJI engine under knocking conditions. Energies. 2024;17(6):1324. https://doi.org/10.3390/en17061324

[22] Singh S., Jain S., et al. Hydrogen: A sustainable fuel for future of the transport sector. Renew Sust Energ Rev. 2015;51:623-633. https://doi.org/10.1016/j.rser.2015.06.040

[23] Tashie-Lewis BC, Nnabuife SG. Hydrogen production, distribution, storage and power conversion in a hydrogen economy – a technology review. Chem Eng J Adv. 2021;8:100172. https://doi.org/10.1016/j.ceja.2021.100172

[24] Tornatore C, Marchitto L, Sabia P, De Joannon M. Ammonia as green fuel in internal combustion engines: state-of-the-art and future perspectives. Frontiers in Mechanical Engineering. 2022;8:944201. https://doi.org/10.3389/fmech.2022.944201

[25] Verhelst S, Wallner T. Hydrogen-fueled internal combustion engines. Prog Energ Combust. 2009; 35(6):490-527. https://doi.org/10.1016/j.pecs.2009.08.001

[26] Wärtsilä Corporation. Product guide. Wärtsilä 25. https://www.wartsila.com/docs/default-source/product-files/engines/df-engine/wartsila-25-brochure.pdf?utm_source=engines&utm_medium=dfengines&utm_term=w25&utm_content=brochure&utm_campaign=mp-engines-and-generating-sets-brochures (accessed on 29.12.2024).

[27] Wärtsilä. Get to know the Wärtsilä 25 ammonia. https://www.wartsila.com/about/190/article/get-to-know-the-wartsila-25-ammonia (accessed on 29.12.2024).

[28] Xu X, Ge C, Zhang B, Ma X, Guo R, Lu X. The degeneration mechanism of lubricating oil in the ammonia fuel engine. Tribology International. 2025; 202:110333. https://doi.org/10.1016/j.triboint.2024.110333

[29] Yousefi A, Guo H, Dev S, Liko B, Lafrance S. Effects of ammonia energy fraction and diesel injection timing on combustion and emissions of an ammonia/diesel dual-fuel engine. Fuel. 2022;314: 122723. https://doi.org/10.1016/j.fuel.2021.122723

[30] Zamfirescu C, Dincer I. Using ammonia as a sustainable fuel. J Power Sources. 2008;185(1):459-465. https://doi.org/10.1016/j.jpowsour.2008.02.097

[31] Zhou L, Zhong L, Liu Z, Wei H. Toward highly-efficient combustion of ammonia-hydrogen engine. Prechamber turbulent jet ignition. Fuel. 2023;352: 129009. https://doi.org/10.1016/j.fuel.2023.129009

[32] Ziółkowski A, Fuć P, Lijewski P, Jagielski A, Bednarek M, Kusiak W. Analysis of exhaust emissions from heavy-duty vehicles on different applications. Energies. 2022;15(21):7886. https://doi.org/10.3390/en15217886