Ammonia as a fuel for means of transport

Dawid Mielcarzewicz[1]*, Ireneusz Pielecha[1]

[1] Faculty of Civil and Transport Engineering, Poznan University of Technology, pl. M. Skłodowskiej-Curie 5, 60-965 Poznań, Poland
* Corresponding author's e-mail: dawid.mielcarzewicz@doctorate.put.poznan.pl

ABSTRACT

The paper provides an overview of the literature on the various techniques for utilising ammonia for fuelling transport means. It discusses the properties of ammonia used in internal combustion engines, as well as its advantages and disadvantages. In addition, the current research trends in ammonia-fuelled compressed (CI) and spark ignition (SI) engines are presented. Particular attention is given to the analysis of the effects of combining ammonia with more reactive fuels. In addition, the possibility of extending the operation of an SI ammonia engine by using a two-stage turbulent jet ignition (TJI) system is explained.

Keywords: ammonia, fuel, combustion, spark ignition, compression ignition, TJI.

INTRODUCTION

Carbon fuels are currently one of main sources of energy. These types of fuels meet approximately 85% of total energy demand. Because of this, around 36 billion tonnes of CO_2 are released into the environment annually (Megía et al., 2021). The transport sector, among others, contributes to this condition: internal combustion engines powered by fossil fuels generate around 25% of the global energy and are responsible for about 17% of worldwide greenhouse gas (GHG) emissions, including carbon dioxide (Onorati et al., 2022). Nowadays, over 95% of the mid- and heavy-duty vehicles in the EU is driven by ICE (Sütheő et al., 2025). Excessive carbon dioxide emissions are a problem, because they amplify the greenhouse effect. According to statistics, the average temperature on Earth is 14°C (Kweku et al., 2018). With its increase, temperatures at both poles also rise, resulting in melting glaciers, which in turn contributes to rising ocean levels. This can lead to devastating storms and tsunamis. In addition, it is predicted that sea levels could rise by up to 7 metres, leading to the flooding of many cities around the world (El Zein and Chehayeb, 2015). In order to avoid the above-mentioned effects of excessive CO_2 emissions, methods of CO_2 capture and utilisation are being researched and developed, as exemplified by a study conducted by (Chan et al., 2025). More important than capturing CO_2 that has already been produced, may be replacing conventional fuels with carbon-free alternatives.

Currently, one of the alternative fuels being considered is ammonia. There are no CO_2 emissions when pure ammonia is burned in an engine. It is extremely important that safety management techniques for large quantities of ammonia are well developed and documented. Many countries have facilities for delivering NH_3 by railway, roads, or via pipelines, so the costs involved in introducing it are expected to be lower than another zero carbon fuel – H_2. Ammonia manufacture was introduced by Bosch and Haber (Kobayashi et al., 2019). For the synthesis of hydrogen from nitrogen their method applies an iron-containing catalyst under elevated pressure (10–30 MPa) and elevated temperature (400–500 °C). The standard Haber-Bosch process utilises the hydrogen derived from steam reforming of methane (Fig. 1).

Production of eco-friendly ammonia, requires the extraction of nitrogen and hydrogen from renewable sources, i.e. through air separation and water electrolysis, respectively. Air separation is the process of separating the components of atmospheric air into its main elements: oxygen,
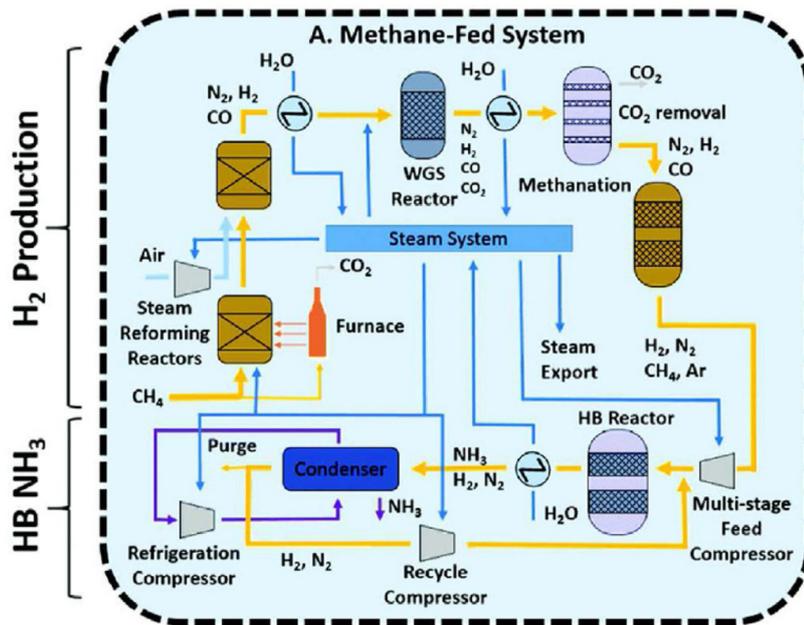
Figure 1. Diagram of a standard Haber-Bosch procedure with the use of methane (Singh et al., 2023)

nitrogen, argon and other gases. Water electrolysis is a chemical process that decomposes water into H_2 and O_2 by using electricity. Besides the conventional Haber-Bosch process, unconventional technologies are also being explored, such as the absorber-enhanced Haber-Bosch process, non-thermal plasma technology, electrochemical synthesis, photochemical synthesis, homogeneous catalysis and chemical loop approaches (Rouwenhorst et al., 2020). The major area of application for ammonia is in the formulation of agro-fertilisers. This has enabled a large increase in food production. Ammonia is also used as a primary material in the manufacture of numerous industrial goods, but also as a refrigerant in large cooling installations (Kobayashi et al., 2019; Rouwenhorst et al., 2020). The above-mentioned reasons make ammonia an economically reasonable alternative combustible material for internal combustion engine (ICE).

CHARACTERISTICS OF AMMONIA FOR ICE

NH_3 is a tetrahedron structure of three atoms H and a lone couple of electrons connected with N. This molecule is characterised by polarity and is strongly connected due to intermolecular hydrogen bonds. Ammonia is a basic, colourless gas with sharp odour. The temperature at which ammonia begins to boil is –33 °C, while the temperature at which ammonia turns into a solid is –77.5 °C. In ambient circumstances, the self-ignition point of NH_3 is 651 °C, a relatively high value which has implications for storage safety. The concentration of ammonia in the atmosphere that poses a direct threat to life or health is 300 ppm. (Dimitriou and Javaid, 2020), but in gaseous state it has a strong odour that can be recognised at much lower concentration – from approximately 5 ppm (Zamfirescu and Dincer, 2008). The energy per unit mass of ammonia is poor compared to other fuels, being 18.6 MJ/kg. However, the amount of energy accumulated in the volume of liquid ammonia exceeds the amount of energy stored in the volume of liquid hydrogen and reaches 12.7 MJ/dm³ (Chai et al., 2021; Aziz et al., 2020). A comparison of the energy characteristics of fuels is presented in Figure 2.

The maximum laminar combustion velocity of ammonia is low and is 0.07 m/s (Aziz et al., 2020). The inflammability spectrum of ammonia extends from 0.63 to 1.4 equivalence ratio, meaning that it can be converted in to excess air ratio of 0.7 to 1.6 (Chai et al., 2021). The heat needed to fire ammonia is comparatively high with a value of 8 mJ (Dimitriou & Javaid, 2020). Table 1 summarises the features of NH_3.

Under ideal ammonia with oxygen combustion conditions, nitrogen, water and heat are
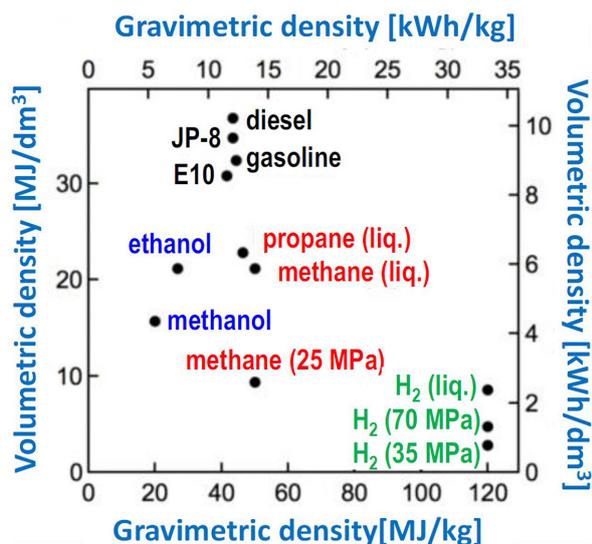
Figure 2. Overview of the energy (calorific) properties of fuels, including ammonia (Hu et al. 2020)

produced – eq. (1). However, during real combustion process, where the fuel burns in the presence of air, the ideal reaction never fully occurs. Incomplete and imperfect combustion results from a variety of factors, such as local oxygen deficiencies, inadequate fuel-air mixing and combustion interruptions (Valera-Medina et al., 2018):

$$4NH_3 + 3O_2 \rightarrow 2N_2 + 6H_2O + heat \quad (1)$$
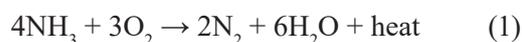
The products of imperfect combustion of an ammonia-air mixture include mainly nitrogen oxides, while incomplete combustion can also result in ammonia in the exhaust gas. The oxidation chemistry of ammonia differs significantly under lean and rich mixture conditions (Fig. 3)

During combustion of a mixture with a large excess of air, a high concentration of O/OH radicals dominates, while HNO works as an indirect link in the creation of fuel NO_x. In contrast, under

combustion of rich mixtures, a significant number of NH_i radicals are generated alongside H radicals, leading to the formation of NNH. Molecular nitrogen (N_2) can be provided via the indirect routes N_2O and NNH, which supports thermal NO_x reduction processes (De-NOx). Ammonia predominantly breaks down via hydrogen abstraction reactions involving H/O/OH radicals, resulting in the creation of NH_2. Pressure, equivalence ratio and temperature influence the oxidation stages of NH_2 and NH. The H_2NO and HNO pathways dominate under conditions of poor mixing and low temperature (upper part of Figure 3), supporting the production of NO_x. In contrast, under higher temperature and rich mixture conditions (lower part of Fig. 3), the reactions with H/NHi radicals and N_2H_i pathways dominate, intensifying De-NOx processes, and reducing NO_x emissions (Elbaz et al., 2022). From the perspective of achieving the lowest possible NO_x emissions, it is most optimal to look for ways of burning ammonia that will ensure a high temperature, which is not easy to achieve with ammonia alone due to its poor flammability properties. Combustion of rich mixtures, on the other hand, can be problematic due to higher unburned ammonia emission. Therefore, it may be beneficial to use ammonia with combination of more reactive fuels.

ADVANTAGES AND DISADVANTAGES OF AMMONIA

It is noteworthy that the main reason for utilising ammonia in ICE is the zero carbon dioxide emissions when it is burned. The key drawback associated with ammonia use is the significant production of NO_x, including N_2O (greenhouse gas). This gas has a relatively high global warming potential (GWP) of 265, compared to 1 for CO_2. Nevertheless, it is important that CO₂, as

Table 1. Ammonia features based on Aziz et al. (2020), Chai et al. (2021) and Dimitriou and Javaid (2020)

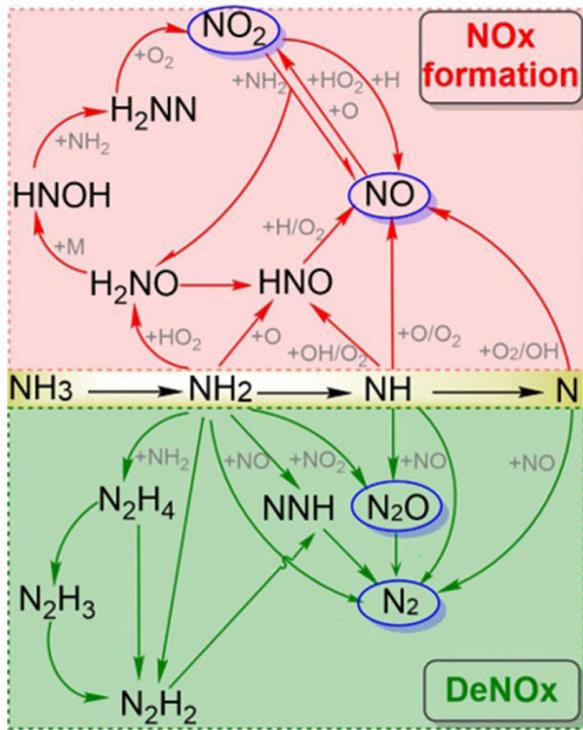| Parameter	Value	Unit
Calorific value	MJ/kg	18.6
Energy density	MJ/L	12.7
Maximum rate of laminar burning	m/s	0.07
Flammability range (λ)	–	0.7–1.6
Flammability range (φ)	–	0.63–1.4
Self-ignition temperature	°C	651
Minimum energy required for ignition of ammonia	mJ	8

Figure 3. NOx creation and the De-NOx chain in a stirred stream reactor, NH_3 oxidation (Elbaz et al., 2022)

the end product of carbon oxidation, does not decompose easily, while N_2O is a transitional compound of nitrogen, it readily breaks down under elevated temperatures, offering the possibility of reducing its emissions through appropriate combustion control strategies and after-treatment systems (Jin et al., 2023).

The most important advantage of ammonia as a fuel is its ease of transport and storage, which make it an economically realistic alternative to carbon-based fuels. Though it occurs as a gas under ambient circumstances, it is generally moved in liquid state via pipelines, tankers, and road tankers. At pressure of 1030 kPa and atmospheric temperature, it is easy to liquefy and store. Another easy solution is to keep it at low temperatures and atmospheric pressure. In this case, ammonia is usually refrigerated to –33 °C, this allows the use of non-pressurised tanks. It is worth mentioning that propane-handling facilities can also be utilised for ammonia in a liquid state. This makes its widespread use as a fuel easier to achieve than in the case of hydrogen (Aziz et al., 2020).

The other major benefit of ammonia is that it may be used as a hydrogen storage medium, as it provides a higher hydrogen concentration per unit volume than liquid hydrogen. An ideal example of the use of this advantage is the propulsion system developed and being refined by Amogy (2025b). The propulsion system uses the hydrogen obtained from ammonia to power fuel cells (Fig. 4). The first stage of this process is to extract the hydrogen from the ammonia, which is then fed into fuel cells that generate electricity to power electric motors. This system was implemented in a drone, then successively scaled up to propel a tractor and then used in a lorry. Currently, the firm utilises the engineered solution to propel vessels.
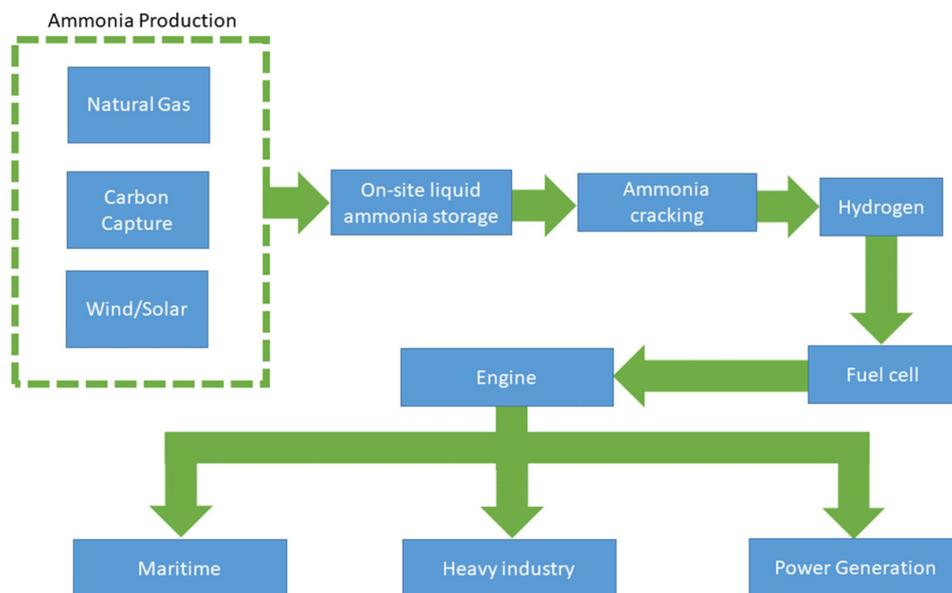

Figure 4. Amogy ammonia to power conversion based on (Amogy, 2025b)

Unlike other fuels, ammonia has the disadvantage of low reactivity. Its high ignition energy, low flammability range and low laminar combustion velocity make it difficult to ignite. The heat accumulated in a mixture of ammonia and air equals 80% of the heat accumulated in a mixture of petrol and air. Consequently, the power of the naturally aspirated (NA) ammonia engine should not exceed 80% of the power of the NA petrol engine. It is difficult to utilise NH_3 in CI engines, because high temperatures are required for it to ignite. The performance of conventional ammonia engines can be improved by the use of modern equipment and modern control systems, such as higher compression ratio, enhanced energy of spark, engine supercharging and fuel blending, e.g. with hydrogen (Kurien and Mittal, 2023).

Another negative aspect of the use of ammonia in internal combustion engines is its corrosive effect on structural materials. The behaviour of metals in an ammonia environment can vary significantly, depending on parameters such as ammonia concentration, temperature and exposure time. Research reveals that high concentrations of ammonia can enhance corrosion, especially for copper and aluminium, although steel has higher corrosion resistance. Stress corrosion cracking is a major degradation of steel under the influence of NH_3. Ammonia can also adversely affect lubricating oil. According to Xu et al. (2025), the solution of NH_3 has the potential to increase the thermal stability and dispersion of oil, while combining the components of additives, resulting in a less wear-resistant characteristic.

A final negative aspect of using ammonia as a fuel is its pungent smell. By incomplete burning of the fuel-air mixture, there will always be trace amounts of ammonia in the exhaust of the engine, the smell of which can be offensive. As it was mentioned earlier, ammonia can be smelled at concentrations of just 5 ppm in air. This implies the necessity of implementing suitable after-treatment systems.

The above mentioned advantages and disadvantages of ammonia show that the manner and scope of its use is still open. Both the arguments for and against its use point to the need for further laboratory and operational research, especially in the context of use in maritime transport.

AMMONIA IN SPARK IGNITION ENGINES

Introduction

Preliminary engines research revealed problems with pure ammonia efficient use in SI engines. This is caused by its low burning characteristics, mentioned earlier. Initial experiments in single cylinder engines showed low thermal efficiency (21% compared with 38% for petrol) and high unburned ammonia emissions. Theoretical analyses suggest that the output of an ammonia engine is about 77% of that fuelled with hydrocarbon fuel (Kurien & Mittal, 2023). Additionally, taking into account that higher temperatures help thermal NO_x reduction processes, it is not surprising that modern research focuses on mixtures of ammonia with gasoline, hydrogen, methane or alcohols. The fuels listed above have better burning features, which boosts the burning rate and engine running stability. Owing to the higher octane value, it is possible to achieve sooner ignition and boost intake pressure, which offsets the power drop related to the low combustion velocity of ammonia (Tornatore et al., 2022). In the consideration of using a dual fuel of ammonia with hydrogen, alcohol or methane, it is important to keep in mind the compromise between optimal engine performance and minimising greenhouse gas emissions. In order to combine the use of the above mentioned fuels in a SI engine, an appropriate fuel injection strategy must be implemented. An example of such strategies is shown in Figure 5.

Thermodynamic and emission aspects of ammonia combustion in SI engines

The thermodynamic performance of the engine and emissions of its combustion products are crucial when considering the use of alternative fuels. Taking into account that the use of ammonia involves mixing it with reactive fuels, it is necessary to search for proportions of the fuel components that provide adequate performance with optimal combustion product emissions. Research aimed at finding such ratios usually compares the binary fuel with the combustion of pure ammonia. Such research was conducted by (Zhu et al., 2024). An ammonia-hydrogen mixture was analysed. The tests were carried out on an dynamometer shown in Figure 6.
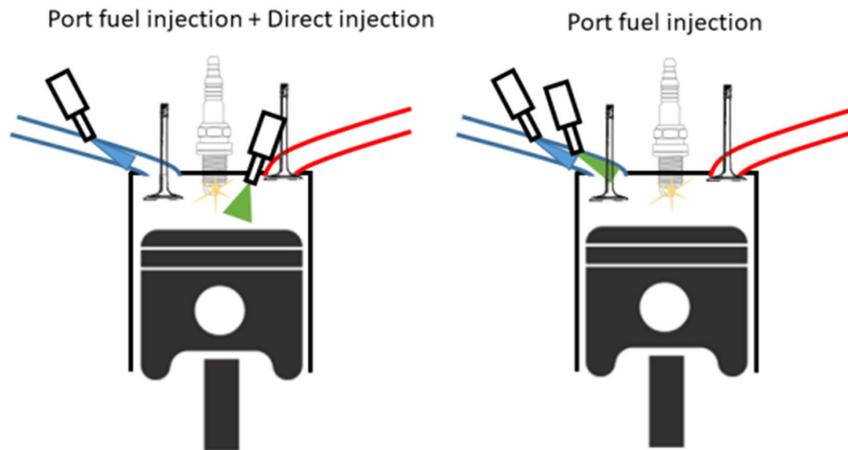
Figure 5. Examples of ammonia and reactive fuel injection strategy in an SI engine: green fuel – ammonia; blue fuel – reactive fuels such as gasoline, hydrogen, ethanol, methane. Based on (Chiong et al., 2021) and (Zhu et al., 2024).
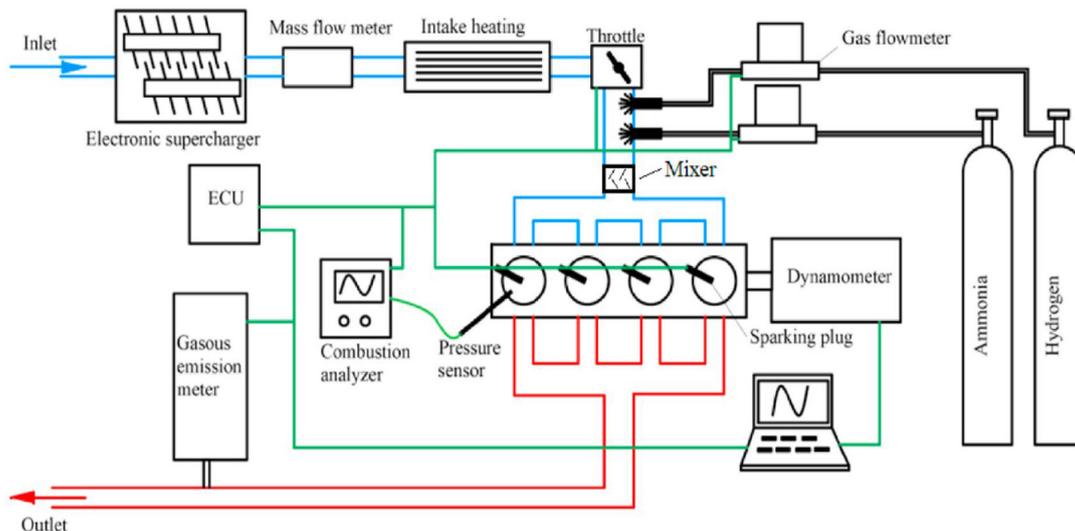

Figure 6. Experimental setup for ammonia-hydrogen engine research (Zhu et al., 2024)

Research shows that stable combustion can be achieved using pure NH_3, but the operational scope of an engine is narrow, in addition, most of the combustion occurs far from TDC. During the test, it was found that raising the hydrogen content causes a higher in-cylinder pressure. This is related to the release of more heat and improved ammonia combustion. The heat release rate can be controlled in ammonia-hydrogen mode, so the maximum value of this parameter occurs closer to top dead centre (TDC) even at low load. This increases thermal efficiency. In summary, hydrogen can be used to increase range of the efficient working of the ammonia engine.

The coefficient of variation of IMEP (CoV_{IMEP}) index in pure ammonia combustion mode reaches much higher value than ammonia combined with hydrogen. For example, in the point of 1000 rpm and 0.4 MPa (BMEP – break mean effective pressure), there is a difference in CoV_{IMEP} of approximately 10%. The study demonstrates that the addition of 5–15% hydrogen solves the unstable combustion of NH_3. Engines that burn pure ammonia have a lower break thermal efficiency (BTE), achieving 33.7% of it. With the addition of 2–16% hydrogen, it is possible to significantly increase engine efficiency, even to 35.8%.

Emissions of harmful compounds in the exhaust gas were also analysed. During the

utilisation of pure NH_3, the minimum unburned concentration of it was 8776 ppm. The addition of hydrogen significantly reduces these figures. Under many conditions, its concentration falls below 5,000 ppm, or even below 3,500 ppm at some point. The addition of hydrogen initially increases the NO_x concentration by increasing the combustion temperature. A further increase in temperature intensifies the reduction reactions of this compound, leading to a decrease in NO_x from a range of 1000–5000 ppm (pure ammonia) to 1000–2600 ppm (ammonia-hydrogen). Emissions of N_2O and unburned ammonia show similar changes. The longer duration of the high temperature helps the decomposition of N_2O. By increasing the percentage of hydrogen, the burning temperature rises, which reduces N_2O emissions (Zhu et al., 2024).

Besides hydrogen, adding methane or ethanol to the mixture with ammonia is also being considered. The research into the engine performance of such combinations was undertaken by Uddeen et al. (2024). The study analysed the effects of methane and ethanol content in ammonia fuel on operating conditions and engine emissions. The results were compared to the combustion of pure ammonia. The dynamometer equipped with an AVL 5402 single cylinder research engine was used (Fig. 7).
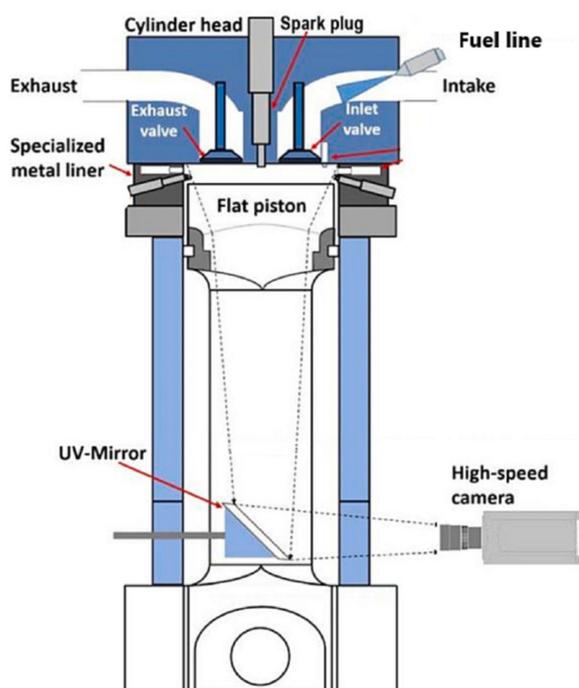

Figure 7. Schematic of a single cylinder engine setup used during ammonia, ethanol, methane research (Uddeen et al., 2024)

As it was shown in Figure 7, a planar extended Bowditch quartz piston was used. The test demonstrates that a 30% addition of ethanol to NH_3 causes a visible rise in combustion pressure. Further increases in its proportion accelerate flame propagation and result in a continued growth in this pressure. The combustion of NH_3 (pure) is characterised by a lower peak HRR and a longer time of burning due to a slower rate of the process. The addition of ethanol accelerates flame propagation, resulting in a higher HRR (Fig. 8).

When methane is combined with ammonia, as in the case of ethanol, increasing the proportion of methane in the mixture leads to an increase of HRR and pressure in the chamber (Fig. 8).

The study also directly compares the ammonia-ethanol with ammonia-methane mixture. The ammonia-ethanol mixture achieved a greater IMEP. The reason for this is the faster flame during ethanol burning. The longer time of the methane-ammonia combustion, led to greater heat loss, giving larger CoV_{IMEP} than ethanol-ammonia. Ethanol provides higher engine efficiency compared to methanol during use with ammonia.

The quoted study also provides the data about the emissions of various pollutants produced by combustion of the abovementioned fuels under the same engine operation. Increasing the proportion of ethanol and methane led to a sharp increase in the concentration of NO_x in exhaust gas. An ammonia-ethanol mixture results in higher NO_x production than an ammonia-methane mixture. A methane-ammonia mixture produces significantly higher unburned hydrocarbon (UHC) emissions than an ethanol-ammonia mixture. Combustion of an ammonia-ethanol mixture resulted in higher CO_2 emissions than combustion of an ammonia-methane mixture (Uddeen et al., 2024).

In summary, hydrogen is the best additive for ammonia dual fuel. Such a mixture ensures adequate efficiency and stability of engine operation. Hydrogen effectively extends the range of engine operation while increasing the combustion temperature and NO_x decomposition. Considering other alternative fuel blends (ammonia-ethanol or ammonia-methane), it appears that ethanol provides greater engine efficiency, more stable operation, higher pressure and higher heat release rate. However, from a greenhouse gas emissions perspective, methane
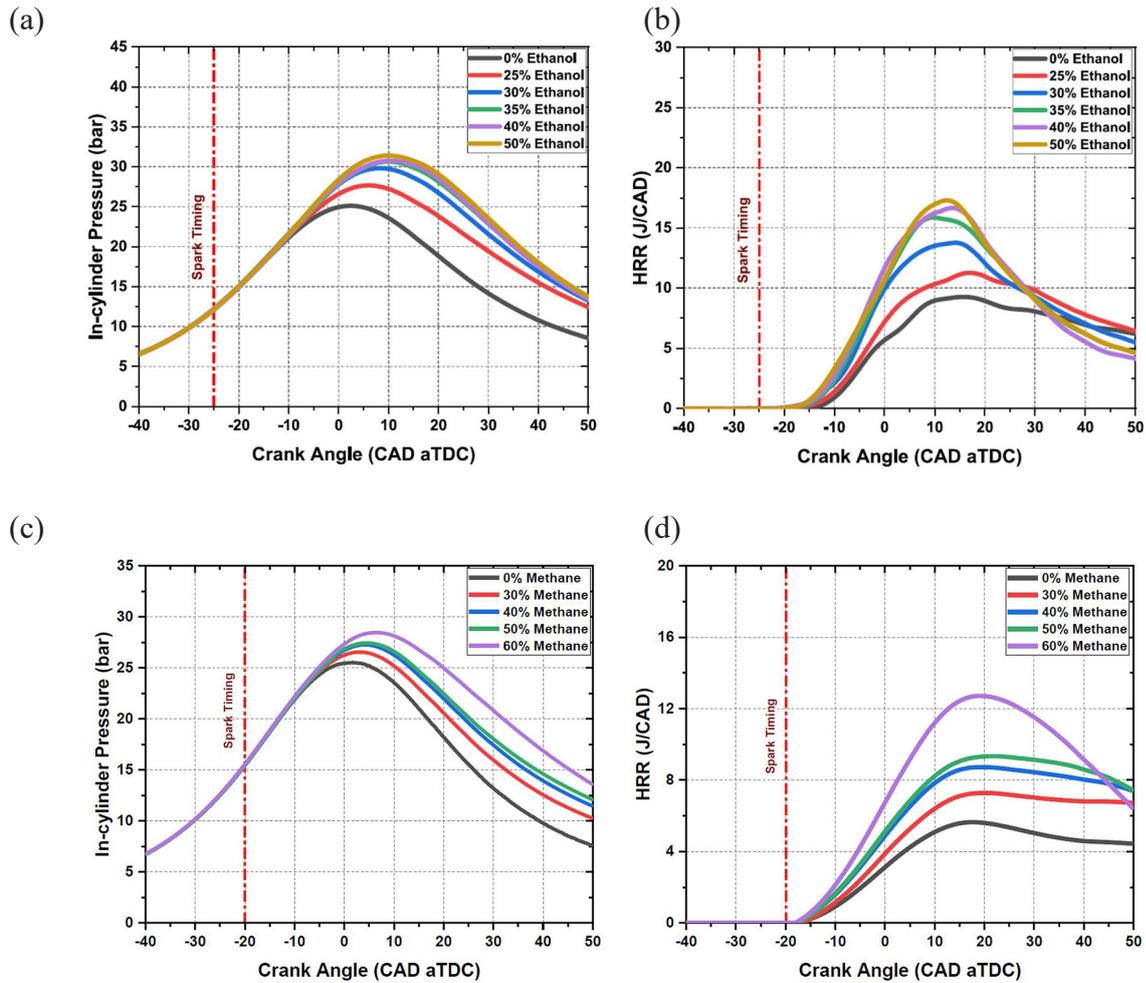
(a)

(b)

(c)

(d)

Figure 8. In-cylinder pressure for different ethanol energy fractions (a) and HRR for different ethanol energy fractions (b) In-cylinder pressure for different methane energy fractions (c) and HRR for different methane energy fractions (d) (Uddeen et al., 2024)

proves to be better option as it provides lower NO_x emissions, including N_2O and CO_2.

AMMONIA IN COMPRESSION IGNITION ENGINES

Due to its adverse combustion properties, pure ammonia is not a suitable fuel for compression ignition engines. Research has shown that successful self-ignition of ammonia in a compression ignition engine requires a very high compression ratio of 35:1 to 100:1, which is significantly higher than standard values (Dimitriou and Javaid, 2020). Currently, CI engines used in heavy duty vehicles operate at compression ratios of 16:1 to 23:1, making the use of ammonia in its pure form impractical. Therefore, research focuses on the use of fuel blends that combine ammonia with diesel. Such a two-component fuel allows

the self-ignition requirements to be lowered. Experiments have shown that such a mixture can be ignited with a compression ratio 15.2:1. The utilisation of NH_3 is now being pushed forward most strongly in the shipping industry, where large-diameter engines are used, which are more appropriate for ammonia (Tornatore et al., 2022). An example of an ammonia and diesel injection strategy is shown in the Figure 9.

Thermodynamic and emission aspects of ammonia combustion in CI engines

When discussing the combination of NH_3 and diesel, it is essential to establish its impact on engine output and emissions. A study of this type was carried out by (Yousefi et al., 2022). During the research, the amount of NH_3 in the two-component fuel was increased and the operating parameters of the diesel engine were analysed. A
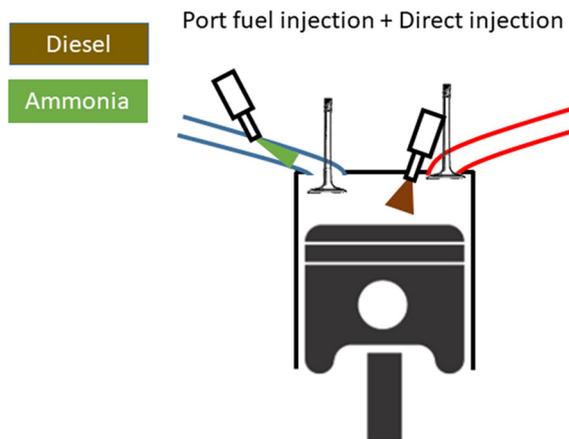
Figure 9. Diesel and ammonia injection strategy based on (Xu et al., 2023)

dynamometer with a single-cylinder engine was used, and it is shown in Figure 10.

The research shows that an increase in the energy content of ammonia in the fuel (AES – ammonia energy share) delays the start of combustion. This is mainly due to the higher temperature at which ammonia can be ignited. The maximum in-cylinder pressure decreases with increasing ammonia energy content. Most of the mixture burns under pre-combustion conditions. It was observed that the growth of AES causes a decrease in indicated thermal efficiency (ITE). This decrease is because of slow combustion, the higher self-ignition temperature of ammonia, and the incomplete combustion of pre-mixed

ammonia-air in the areas away from the fuel jet (Yousefi et al., 2022).

When knowing how NH_3 in the dual fuel affects the thermodynamic parameters of the CI engine, it is important to find out how its emissions of harmful components change. The answer to this question can be found in the research work of (Nadimi et al., 2023). Experiments were carried out on a test bench shown in Figure 11.

The study shows that increasing the content of NH_3 in relation to diesel significantly reduces CO and CO_2 emissions, while increasing the H_2O content of the exhaust gases. This is because diesel is a hydrocarbon fuel, while the combustion of ammonia with air produces nitrogen, water and heat (under ideal conditions). During the analysis, it was observed that NO emission initially decrease and then increase with increasing ammonia (Fig. 12). Further increases in AES (ammonia energy share) lead to higher NO emission. This is due to the fact that NO creation relies on both the existence of nitrogen in NH_3 and the in-cylinder temperature.

During the analysis of N_2O emission, a negative effect of ammonia was observed. The combustion of only diesel led to an exhaust gas N_2O concentration of around 3 ppm, while immediately after the ammonia injection, the concentration of this component rises sharply to 90 ppm. Then, it drops to 42 ppm at higher AES. The concentration of unburned NH_3 increased with the rise of AES to a critical level of 14.800 ppm at
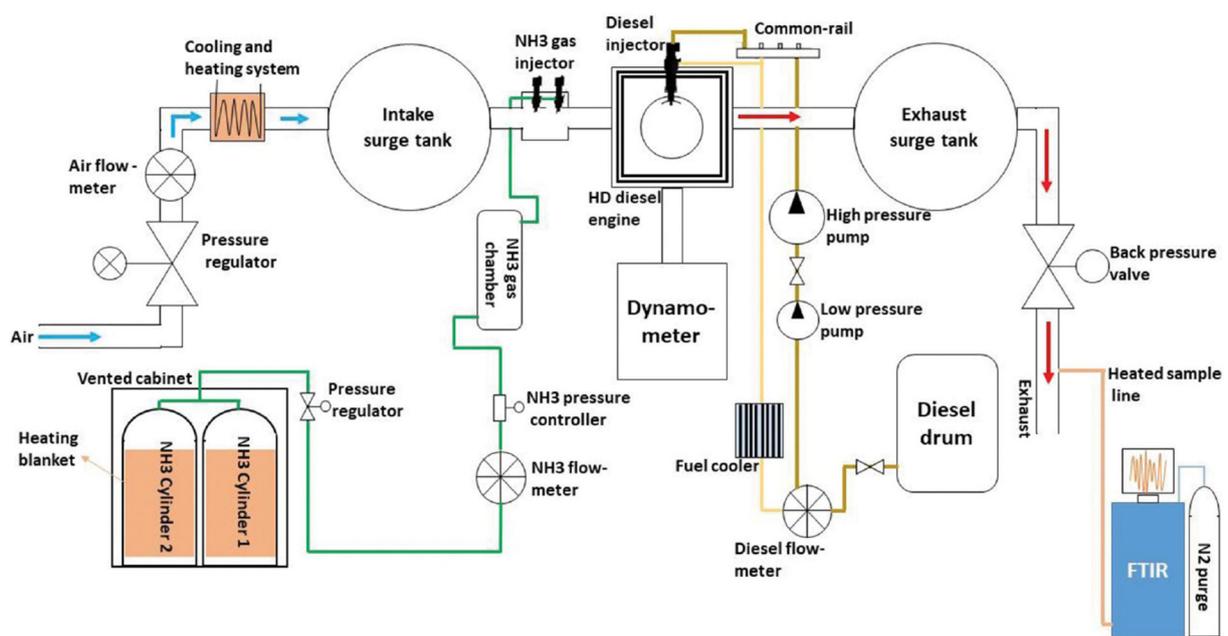

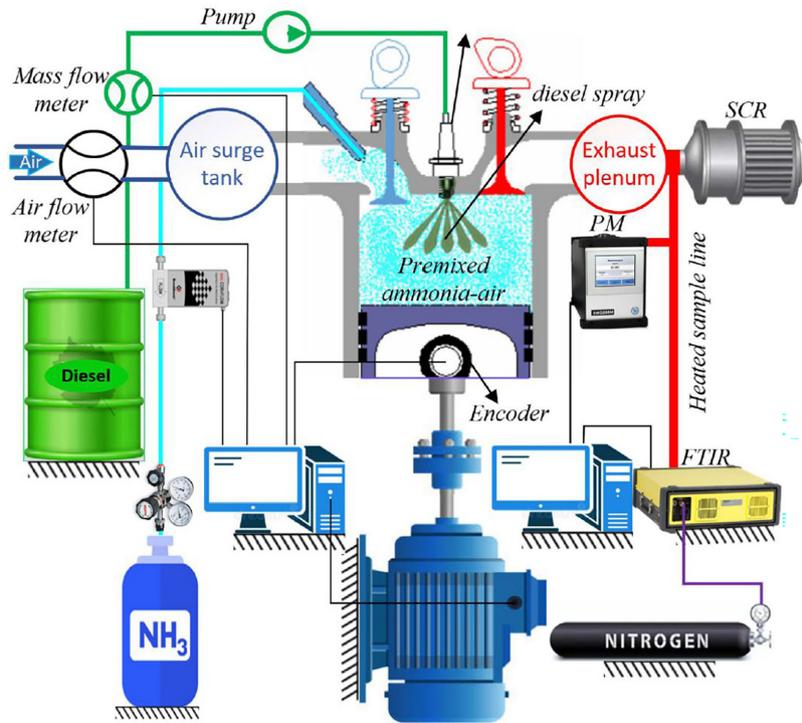**Figure 10.** Dynamometer with ammonia CI engine (Yousefi et al., 2022)

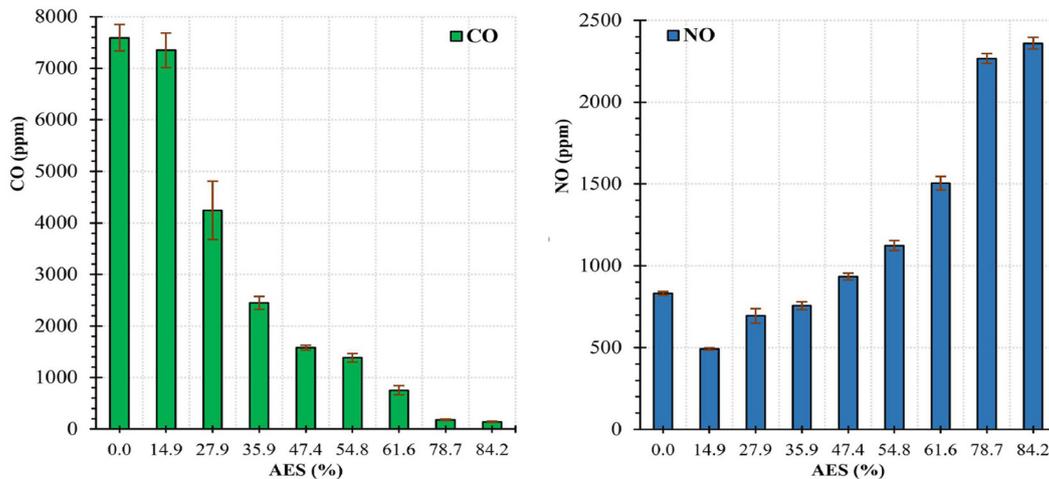**Figure 11.** Test rig with ammonia CI engine (Nadimi et al., 2023)

Figure 12. Impact of NH_3 on (a) CO and (b) NO emissions (Nadimi et al., 2023)

maximum AES. The reason for this is the surplus of ammonia in the cylinder, which leads to a high level of unburned fuel. In addition, due to the slow ammonia combustion speed, incomplete flame propagation occurs, often resulting in unburned fuel remaining. In addition, the study showed that the peak AES at which diesel could be replaced was 84.2%. At higher ammonia contents, the engine does not run properly (Nadimi et al., 2023).

To summarise, the performance indicators of an engine that runs on ammonia and diesel are poorer than those of a diesel engine. This is caused by slow flame propagation and high start of combustion temperature of NH_3. A benefit of burning dual-component mixture is the reduced CO_2 emissions. However, the weakness of CI engines running on ammonia and diesel is higher emissions of unburned NH_3 and NO_x, including N_2O (a greenhouse gas). It should be remembered that N_2O, as a nitrogen intermediate, is easily decomposed at high temperatures, providing an opportunity to reduce emissions of this compound through appropriate combustion control strategies and exhaust after-treatment systems.

TWO STAGE COMBUSTIONION – TURBULENT JET IGNITION

Turbulent jet ignition, a two-stage combustion system, represents an attractive improvement to the weak burning characteristics of ammonia. Two chambers are a characteristic feature of this type of engine (pre- and main chambers). The spark plug is installed in the pre-chamber, the volume of which typically comprises less than 5% of the engine clearance volume (Silva et al., 2022). The fuel-air mixture is ignited in the pre-chamber, and then the flames passing through the orifices to the main chamber initiate the ignition of the rest of the mixture. There are two types of pre-chamber depending on the fuelling strategy: passive and active (Huang et al., 2023). In the passive chamber, the fuel is not supplied directly to the pre-chamber, the fuel-air mixture enters it from the main chamber through orifices. Fuel in the active system, on the other hand, is injected directly into pre-chamber via a separate injector located inside it. Both systems are shown in Figure 13.

The active TJI system is a promising solution for improving ammonia combustion, as it allows the reactive fuel to be used in the pre-chamber, helping to ignite ammonia or mixtures with ammonia in the main chamber. According to (Liu et al., 2023), a TJI engine fed with ammonia and a more reactive fuel shows enhanced burn stability, higher IMEP, and accelerated combustion compared to a standard SI engine. Furthermore, use of TJI results in lower NO_x and unburned NH_3 emissions compared to standard SI, especially if hydrogen is fed into the pre-chamber (Fig. 14).

According to a computational fluid dynamics (CFD) simulation by Huo et al., (2024) in active hydrogen-fuelled pre-chamber mode, higher mixture reactivity increases the tendency for fuel self-ignition and knock combustion. In addition, it was concluded that, as both the proportion of hydrogen and the equivalence ratio increase, the production of nitrogen oxide rises.

It is noteworthy that the performance and emission of a TJI engine depend not only on the composition of the fuel-air mixture, but also on the geometry of the pre-chamber, the number of orifices and their diameter. According to a study by Antolini et al. (2023), the diameter of the pre-chamber orifices influences the flame formation characteristics, which also has a consequence on the combustion in the main chamber. The results show that for smaller pre-chamber orifices, the time between spark in the pre-chamber and ignition of the mixture in the main chamber is longer than for larger diameter orifices (Fig. 15). Methane was used during this test, but it is clear that in the case of ammonia, the parameters above may also affect the parameters of the flame leaving the combustion chamber, which creates the need to conduct appropriate research.

The direct effect of the pre-chamber volume of TJI engine on the combustion characteristics was investigated by Cui et al. (2022). The larger pre-chamber caused earlier jet appearance and lower ignition delay due to reduced heat release rate (HRR).
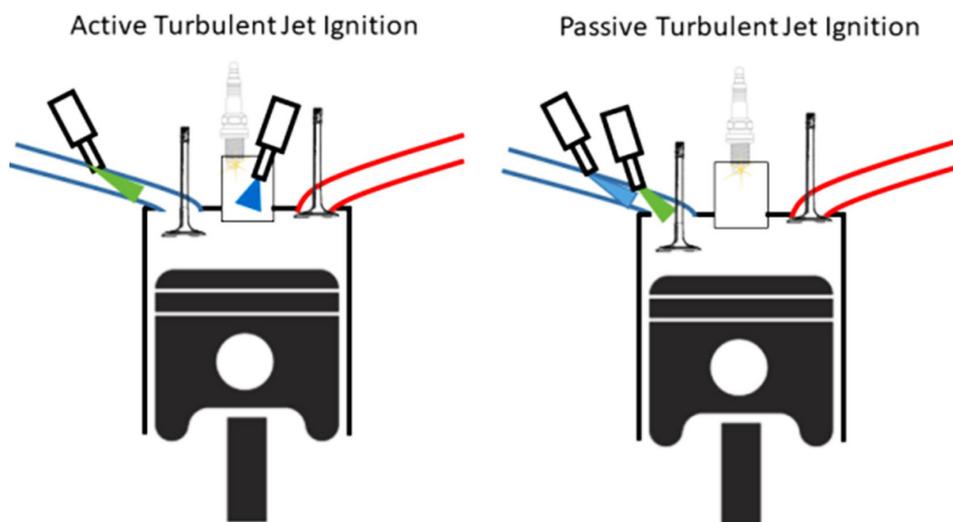

Figure 13. Active and passive TJI injection strategy: green fuel – ammonia; blue fuel – reactive fuels uch as gasoline, hydrogen, ethanol, methane based on (Zhu et al., 2022).
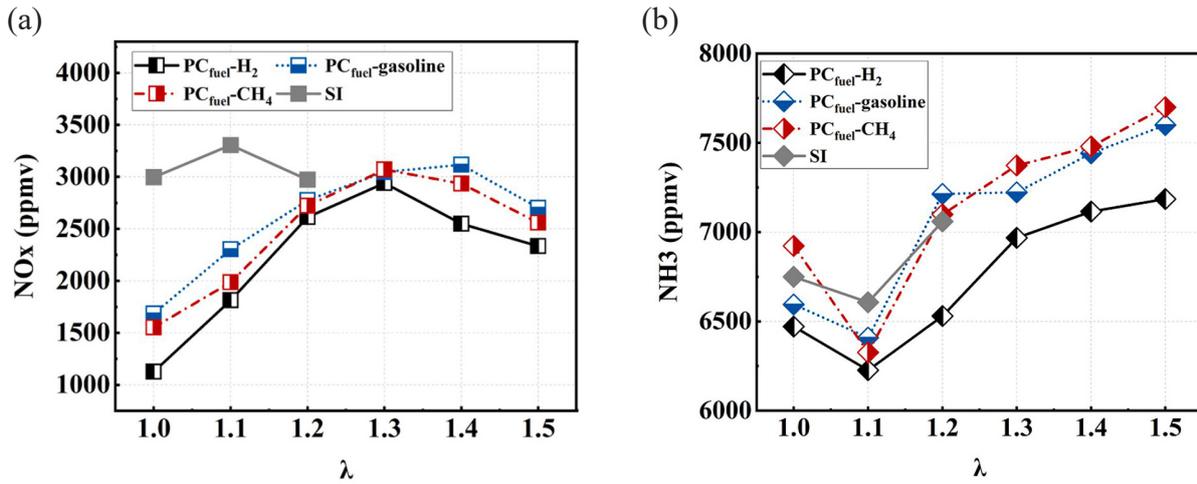
(a)

(b)

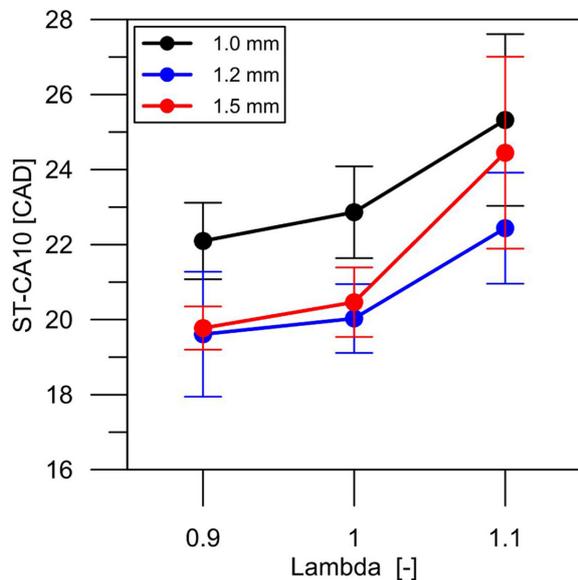**Figure 14.** NO$_x$ (a) and NH$_3$ (b) emissions for different fuels injected into pre-chamber (Liu et al., 2023)

Figure 15. Flame development angle for 1.0, 1.2 and 1.5 mm prechamber ignition concept configurations at λ = 0.9, 1.0 and 1.1 at maximum brake torque (MBT) condition (Antolini et al., 2023)

The research of applying the TJI two-stage combustion system to ammonia is an interesting and promising direction for the development of engine technology. The use of this method can contribute to improving the efficiency of ammonia combustion, increasing the stability of the ignition process and reducing harmful emissions. Further research in this area may open up new opportunities for low-emission powertrains, which is crucial in the context of global efforts to reduce greenhouse gas emissions

CONCLUSIONS

Ammonia, which is a fuel that does not contain carbon, is proving to be an economically realistic replacement for hydrocarbon fuels, due to the production and transport infrastructure that already exists. Analysis of NH$_3$ properties as a fuel shows that its use remains open and still requires further research. Due to its inefficient burning characteristics, the application of NH$_3$ in both SI and CI engines has focused on mixing it with more reactive fuels.

For SI engines, the research focuses mainly on ammonia with hydrogen, ethanol, or methane use. The most beneficial combination in terms of greenhouse gas emissions is ammonia-hydrogen, as these are carbon-free fuels. Hydrogen effectively extends the operating range of the engine while increasing the combustion temperature of the process. Considering ammonia-ethanol or ammonia-methane, it appears that ethanol provides greater engine efficiency, more stable operation, higher pressure and higher heat release rate. However, from a greenhouse gas emissions perspective, methane is the better option, as it provides lower NO$_x$ emissions, including N$_2$O and CO$_2$. An interesting way to improve the poor combustion properties of ammonia is to use a two-stage combustion Turbulent Jet Ignition system. The use of this method can improve the combustion efficiency of ammonia, increase the stability of the ignition process, extend the range of flammability, and reduce emissions of harmful exhaust components.

In compression ignition engines, ammonia can be used as a dual fuel with diesel. Marine

transport is a major contributor to the use of such a blend. The presented research reveals that the diesel-ammonia engine performance is poorer than pure diesel engine. Among other things, this is a result of the high ignition temperature and slow flame propagation of ammonia. The use of binary fuels offers the advantage of reduced carbon dioxide emissions. However, the major drawback of burning ammonia and diesel is the higher emissions of unburned NH_3 and N_2O, which is also a greenhouse gas. The key point is that N_2O breaks down readily at elevated temperatures, which helps to minimise its emissions.

Acknowledgements

REFERENCES

1. Amogy. (2025b). Ultra-efficient ammonia-to-power conversion (accessed on 26.08.2025). https://amogy.co/about/technology

2. Antolini, J., Sementa, P., Tornatore, C., Catapano, F., Vaglieco, B.M., Desantes, J.M., & López, J.J. (2023). Effect of passive pre-chamber orifice diameter on the methane combustion process in an optically accessible SI engine. *Fuel, 341*, 126990. https://doi.org/10.1016/j.fuel.2022.126990

3. Aziz, M., Wijayanta, A.T., & Nandiyanto, A.B.D. (2020). Ammonia as effective hydrogen storage: a review on production, storage and utilization. *Energies*, *13*(12), 3062. https://doi.org/10.3390/en13123062

4. Chai, W.S., Bao, Y., Jin, P., Tang, G., & Zhou, L. (2021). A review on ammonia, ammonia-hydrogen and ammonia-methane fuels. *Renewable and Sustainable Energy Reviews*, *147*, 111254. https://doi.org/10.1016/j.rser.2021.111254

5. Chan, R.Y., Zeng, Y.Z., Hou, C.C., Kuo, H.C., & Huang, H.W. (2024). Experimental study of carbon dioxide capture and mineral carbonation using sodium hydroxide solution. *Journal of Ecological Engineering, 26*(1)*, 30–45*. https://doi.org/10.12911/22998993/195214

6. Chiong, M.C., Chong, C. T., Ng, J.-H., Mashruk, S., Chong, W. W. F., Samiran, N. A., Mong, G. R., & Valera-Medina, A. (2021). Advancements of combustion technologies in the ammonia-fuelled engines. *Energy Conversion and Management, 244*, 114460. https://doi.org/10.1016/j.enconman.2021.114460

7. Cui, Z., Tian, J., Zhang, X., Yin, S., Long, W., & Song, H. (2022). Experimental study of the effects of pre-chamber geometry on the combustion characteristics of an ammonia/air pre-mixture ignited by a jet flame. *Processes*, *10*(10), 2102. https://doi.org/10.3390/pr10102102

8. Dimitriou, P., & Javaid, R. (2020). A review of ammonia as a compression ignition engine fuel. *International Journal of Hydrogen Energy*, *45*(11), 7098–7118. https://doi.org/10.1016/j.ijhydene.2019.12.209

9. Elbaz, A.M., Wang, S., Guiberti, T.F., & Roberts, W.L. (2022). Review on the recent advances on ammonia combustion from the fundamentals to the applications. *Fuel Communications*, *10*, 100053. https://doi.org/10.1016/j.jfueco.2022.100053

10. El Zein, A.L., Chehayeb N.A. (2015). The effect of greenhouse gases on earth's temperature. *International Journal of Environmental Monitoring and Analysis*, *3*(2), 74–79. https://doi.org/10.11648/j.ijema.20150302.16

11. Hu, G., Chen, C., Lu, H. T., Wu, Y., Liu, C., Tao, L., ... & Li, K. G. (2020). A review of technical advances, barriers, and solutions in the power to hydrogen (P2H) roadmap. *Engineering, 6*(12)*, 1364-1380*. https://doi.org/10.1016/j.eng.2020.04.016

12. Huang, L., Tang, Q., Sun, J., & Yao, M. (2023). Numerical study of the effects of excess air ratio on passive pre-chamber jet performance and ignition mechanism. *Applied Thermal Engineering*, *234*, 121315. https://doi.org/10.1016/j.applthermaleng.2023.121315

13. Huo, J., Zhao, T., Lin, H., Li, J., Zhang, W., Huang, Z., & Han, D. (2024). Study on lean combustion of ammonia-hydrogen mixtures in a pre-chamber engine. Fuel, 361, 130773. https://doi.org/10.1016/j.fuel.2023.130773

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

15. Jolaoso, L., & Zaman, S.F. (2020). Catalytic ammonia decomposition for hydrogen production: utilization of ammonia in a fuel cell. In: Inamuddin, Boddula, R., Asiri, A. (eds) Sustainable ammonia production. green energy and technology. Springer, Cham. https://doi.org/10.1007/978-3-030-35106-9_5

16. Kobayashi, H., Hayakawa, A., Somarathne, K.D.K.A., & Okafor, E.C. (2019). Science and technology of ammonia combustion. *Proceedings of the Combustion Institute*, *37*(1), 109–133. https://doi.org/10.1016/j.proci.2018.09.029

17. Kurien, C., & Mittal, M. (2023). Utilization of green ammonia as a hydrogen energy carrier for decarbonization in spark ignition engines. *International Journal of Hydrogen Energy*, *48*(74), 28803–28823. https://doi.org/10.1016/j.ijhydene.2023.04.073

18. Kweku, D., Bismark, O., Maxwell, A., Desmond, K., Danso, K., Oti-Mensah, E., Quachie, A., & Adormaa, B. (2018). Greenhouse effect: greenhouse gases and their impact on global warming. *Journal of Scientific Research and Reports*, *17*(6), 1–9. https://doi.org/10.9734/JSRR/2017/39630

19. Liu, Z., Zhou, L., Zhong, L., & Wei, H. (2023). Enhanced combustion of ammonia engine based on novel air-assisted pre-chamber turbulent jet ignition. *Energy Conversion and Management*, *276*, 116526. https://doi.org/10.1016/j.enconman.2022.116526

20. Megía, P.J., Vizcaíno, A.J., Calles, J.A., & Carrero, A. (2021). Hydrogen production technologies: from fossil fuels toward renewable sources. a mini review. *Energy & Fuels*, *35*(20), 16403–16415. https://doi.org/10.1021/acs.energyfuels.1c02501

21. Nadimi, E., Przybyła, G., Lewandowski, M.T., & Adamczyk, W. (2023). Effects of ammonia on combustion, emissions, and performance of the ammonia/diesel dual-fuel compression ignition engine. *Journal of the Energy Institute*, *107*, 101158. https://doi.org/10.1016/j.joei.2022.101158

22. Onorati, A., Payri, R., Vaglieco, B., Agarwal, A., Bae, C., Bruneaux, G., Canakci, M., Gavaises, M., Günthner, M., Hasse, C., Kokjohn, S., Kong, S.-C., Moriyoshi, Y., Novella, R., Pesyridis, A., Reitz, R., Ryan, T., Wagner, R., & Zhao, H. (2022). The role of hydrogen for future internal combustion engines. *International Journal of Engine Research*, *23*(4), 529–540. https://doi.org/10.1177/14680874221081947

23. Rouwenhorst K.H.R., Krzywda P.M., Benes N.E., Mul, G., & Lefferts, L. (2020). Ammonia production technologies. In Valera-Medina A., & Banares-Alcantara, R. (eds.), Techno-economic challenges green ammonia as an energy vector. Academic Press. https://doi.org/10.1016/B978-0-12-820560-0.00004-7

24. Sütheő, G., Jagicza, M., & Baráth, B. (2025). Emission analysis of liquefied natural gas and diesel heavy-duty trucks using on-board monitoring method. *Journal of Ecological Engineering, 26(2)*, 258–271. https://doi.org/10.12911/22998993/195574

25. Silva, M., Liu, X., Hlaing, P., Sanal, S., Cenker, E., Chang, J., Johansson, B., & Im, H.G. (2022). Computational assessment of effects of throat diameter on combustion and turbulence characteristics in a pre-chamber engine. *Applied Thermal Engineering*, *212*, 118595. https://doi.org/10.1016/j.applthermaleng.2022.118595

26. Singh, S., Mohammed, A.K., AlHammadi, A.A., Shetty, D., & Polychronopoulou, K. (2023). Hypes and hopes on the materials development strategies to produce ammonia at mild conditions. *International Journal of Hydrogen Energy*, *48*(89), 34700–34739. https://doi.org/10.1016/j.ijhydene.2023.05.206

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

28. Uddeen, K., Tang, Q., Shi, H., & Turner, J. (2024). Performance and emission analysis of ammonia-ethanol and ammonia-methane dual-fuel combustion in a spark-ignition engine: an optical study. *Fuel*, *358*, 130296. https://doi.org/10.1016/j.fuel.2023.130296

29. Valera-Medina, A., Xiao, H., Owen-Jones, M., David, W.I.F., & Bowen, P.J. (2018). Ammonia for power. *Progress in Energy and Combustion Science*, *69*, 63–102. https://doi.org/10.1016/j.pecs.2018.07.001

30. Xu, L., Xu, S., Bai, X.-S., Repo, J. A., Hautala, S., & Hyvönen, J. (2023). Performance and emission characteristics of an ammonia/diesel dual-fuel marine engine. *Renewable and Sustainable Energy Reviews, 185*, 113631. https://doi.org/10.1016/j.rser.2023.113631

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

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

33. Zamfirescu, C., & Dincer, I. (2008). Using ammonia as a sustainable fuel. *Journal of Power Sources*, *185*(1), 459–465. https://doi.org/10.1016/j.jpowsour.2008.02.097

34. Zhu, S., Akehurst, S., Lewis, A., & Yuan, H. (2022). A review of the pre-chamber ignition system applied on future low-carbon spark ignition engines. *Renewable and Sustainable Energy Reviews, 154*, 111872. https://doi.org/10.1016/j.rser.2021.111872

35. Zhu, T., Yan, X., Gao, Z., Qiu, Y., Zhu, L., & Huang, Z. (2024). Combustion and emission characteristics of ammonia-hydrogen fueled SI engine with high compression ratio. *International Journal of Hydrogen Energy*, *62*, 579–590. https://doi.org/10.1016/j.ijhydene.2024.03.035