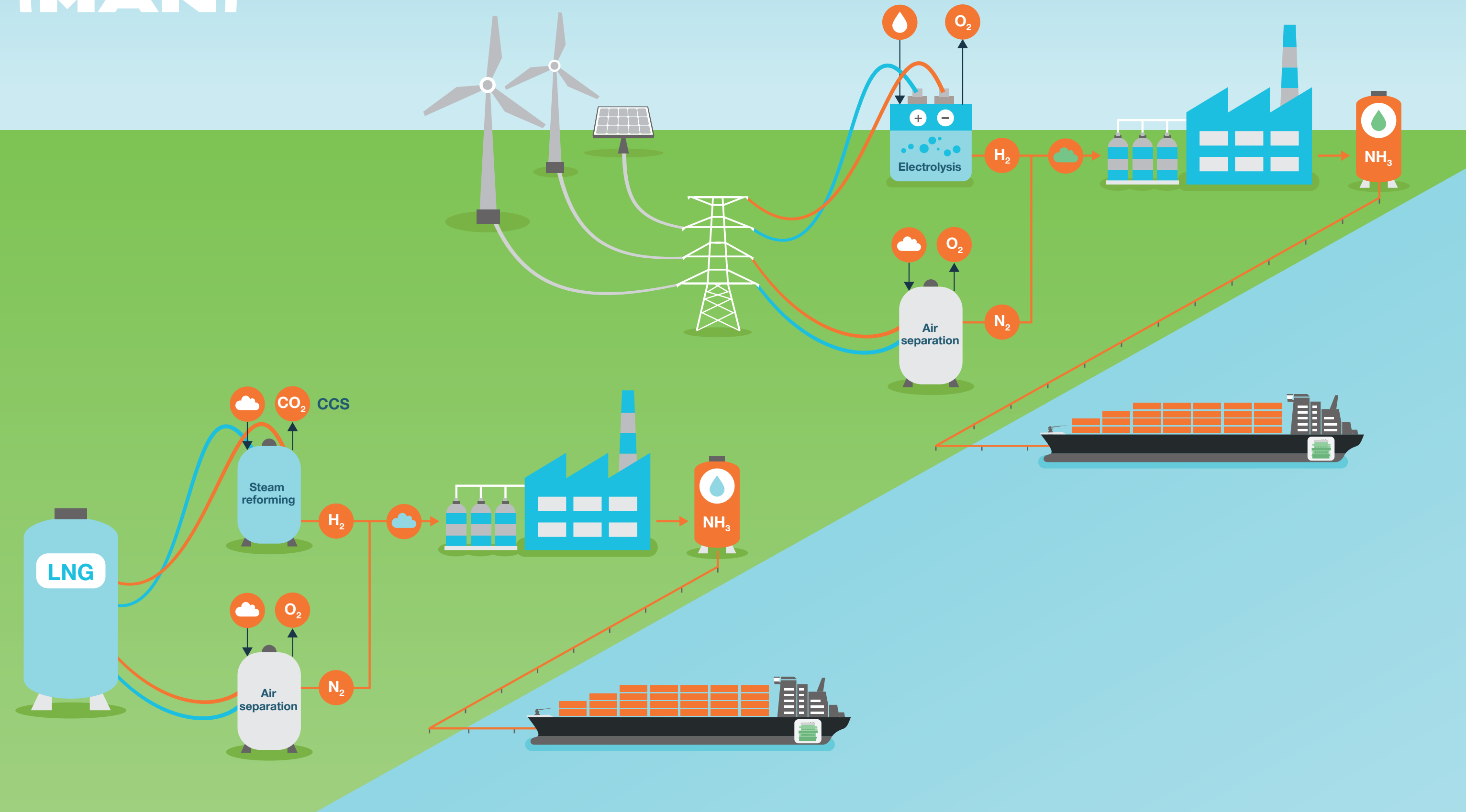


MAN B&W two-stroke engine operating on ammonia

MAN Energy Solutions
Future in the making

Future in the making

Contents

Ammonia as a marine fuel is put into perspective as this paper presents our current knowledge about ammonia as a potential long-term fuel for two-stroke marine engines. We address the challenges encountered by the maritime market, which are best described as a paradigm shift to ensure compliance with global decarbonisation goals.

To develop an engine for a new fuel such as ammonia calls for partnerships, cooperation and an understanding of the market interests. MAN Energy Solutions works diligently towards designing the MAN B&W engine for operation on ammonia and offering retrofit conversions of existing two-stroke engines to ammonia.

Decarbonisation constitutes one of the largest transitions encountered, and the short deadline to succeed requires a united and committed approach from the entire supply chain from well to wake.

1. Introduction

One of the future fuel candidates receiving a growing global interest and likely to play a significant role in the decarbonisation is ammonia (NH_3). Our aim with this paper is to share our current knowledge about ammonia as a potential long-term fuel for two-stroke marine engines and to give a new update on the development of an ammonia-based propulsion.

Thanks to the carbon- and sulphur-free molecular composition of NH_3, combusting it in an engine creates near-zero CO_2 and SO_X emissions. From a well-to-wake perspective, ammonia becomes a carbon-neutral fuel when produced from renewable energy sources like electricity produced from hydropower, wind or solar energy. Furthermore, emissions of air pollutants related to carbon (black carbon or soot, unburned hydrocarbons (HC), methane slip, and carbon monoxide (CO)) are eliminated.

One of the characteristics defining the two-stroke engine portfolio of MAN Energy Solutions in Fig. 1 is the fuel diversity.

Another distinctive feature is the ability to operate on almost any fuel or fuel quality with no or limited decrease in efficiency and with the reliable performance and operating characteristics as the conventional two-stroke engine even in adverse weather conditions.

The fundamental reasons for the large tolerance to poorly ignitable and burning fuels are the low speed of the engine, allowing time for the combustion to finish, and the large dimensions, leading to large volume-to-surface ratios, which is beneficial for a complete combustion and low wall heat losses.

The beneficial carbon-free nature of ammonia also implicates that ammonia combustion physics will not fully resemble the combustion characteristics of previously known two-stroke fuels. To provide our customers with an optimised and reliable engine of the well-known standard of MAN Energy Solutions, it is vital to research the entire propulsion solution and two-stroke engine processes, that is, ignition, combustion and emissions as well as fuel handling.

Therefore, research of ammonia as a fuel for two-stroke engines involves extensive testing with a complete engine monitoring setup to achieve fundamental information about, for example, the ignition properties of ammonia in a two-stroke engine, pilot fuel requirements and emissions. These research results will govern the final design of the ammonia-burning engine and auxiliary systems.

Fig. 1: MAN B&W dual-fuel two-stroke engine portfolio

2. United effort towards a future decarbonising fuel

At MAN Energy Solutions, we are committed to optimise the environmental impact of our engines. To develop an engine for new fuels such as ammonia calls for partnerships and an understanding of the market interests. An analysis of the actual potential is also essential before starting the development of the ammonia engine. In this case, the fuel can enter the market as an intermediate fuel until green ammonia is available and the logistics are in place.

Minimising the impact of shipping on the climate and the environment is a crucial contribution to reaching the global climate targets. One of the ultimate goals would be carbon-neutral transportation. Currently, worldwide maritime transport emits around 3% of the global greenhouse gas (GHG) emissions. Like other industries, the marine industry must decarbonise, and the International Maritime Organization (IMO) has set a target of net-zero CO_2 emissions from shipping by 2050.

Another uncertain and most essential parameter in the decision of the future fuel is the prices of the future fuels. On the one hand, if green ammonia was available today, it would be several times more expensive than very-low-sulphur fuel oil (VLSFO) and LNG. On the other hand, we acknowledge that the marine market widely understands that if CO_2 and GHG footprints are to be reduced for the foreseeable future, some kind of international regulation of the CO_2 and GHG emissions needs to come into force.

We have entered into commitments with other players to investigate the opportunity for ammonia as the coming future fuel and hydrogen carrier.

In this connection, we are happy to announce that the Innovation Fund Denmark has decided to support the development within the framework of the project AEngine, the project's aim being the design and demonstration of an ammonia-based propulsion system. MAN Energy Solutions is the AEngine project coordinator and a part of the cross-functional project team together with Eltronic FuelTech (fuel supply systems), the Technical University of Denmark and the classification society DNV GL [1].

MAN Energy Solutions will integrate existing technology in the ammonia-based propulsion system while designing the ammonia fuel injection, combustion components, exhaust gas after-treatment technology and engine components. In addition, MAN Energy Solutions will provide the engine test bed and conduct the engine trial run.

As a step on the transition path towards decarbonisation, Maersk, MAN Energy Solutions and five partners have joined forces in launching the Maersk Mc-Kinney Moller Center for Zero Carbon Shipping in Copenhagen [2]. Brian Østergaard Sørensen, Vice President and Head of R&D Two-Stroke Business at MAN Energy Solutions, has framed the nature and successful progress of the present task:

"Decarbonisation will be one of the largest transitions that we will see within the maritime industry for years and requires a holistic approach looking at the complete supply chain from well to wake. No technology or company can do this alone, which is why we need to join forces across the supply chain to meet this challenge. We at MAN Energy Solutions have decarbonisation as part of our corporate strategy, and developing sustainable technologies and solutions is at the core of what we do. While two-stroke engine technology will likely remain the prime mover for deep-sea shipping, cleaner fuels will play a larger role in the future. MAN Energy Solutions recognises that there are several pathways to achieving a carbon-neutral economy and that we need to work together, which is why we are happy to have joined the Center."

The Maersk Mc-Kinney Moller Center for Zero Carbon Shipping will be an independent research centre, bringing together stakeholders from the shipping sector, industry, academia and authorities. A highly specialised, cross-disciplinary team will collaborate globally to create overviews of decarbonisation pathways, accelerate the development of selected decarbonising fuels and powering technologies, and support the establishment of regulatory, financial, and commercial means to enable the transformation.

Furthermore, besides working closely together with our licensee Mitsui Engineering & Shipbuilding in a partnership agreement we also work together with different universities.

3. Reflections on ammonia as a future two-stroke marine fuel

Physical/chemical properties of ammonia govern many of the design aspects of an ammonia-fuelled propulsion system and auxiliary systems, including storage.

Vessel owners have to consider ammonia storage and availability, vessel trade pattern and related emission regulations combined with an increased focus on the environmental impact of the vessels.

3.1 Physical properties

Generally, ammonia is produced via the Haber-Bosch synthesis process from hydrogen and nitrogen. While the nitrogen comes from air separation, several production routes can be used to produce hydrogen, most prominently from steam reforming of hydrocarbons or from electrolysis of water, as outlined in more detail below.

For comparison, Table 1 shows the physical properties of ammonia, other alternative fuels, and MGO.

Currently, parameters for fuel supply and injection pressures for NH_3 are 80 bar and 600–700 bar, respectively. However, these parameters make up the topics of further research and optimisation in the engine test scheme.

A comparison of the properties related to storage in Table 1 shows that hydrogen (H_2) liquefies when cooled to temperatures below -253°C, and LNG at -162°C. By contrast, ammonia liquefies already at -33°C.

Liquid ammonia can be stored at a pressure above 8.6 bar at ambient temperature (20°C). To keep it in the liquid phase if the ambient temperature increases, it is common to design non-refrigerated ammonia tanks for approximately 18 bar.

3.2 Transition towards green ammonia production

Although it is in the nature of things that combustion of ammonia emits no CO_2, as it contains no carbon atoms, large-scale industrial productions of ammonia are based mainly on a fossil fuel feedstock for grey and blue ammonia production. This conventional ammonia production produces CO_2 as a by-product. Blue ammonia production involves capture of the generated CO_2, which is liquefied and stored using the carbon capture and storage (CCS) principles.

Energy storage type/chemical structure	Energy content, LHV	Energy density	Fuel tank size relative to MGO	Supply pressure	Emission reduction compared to HFO Tier II [%]			
	[MJ/kg]	[MJ/L]		[bar]	SO_X	NO_X	CO_2	PM
Ammonia (NH_3) (liquid, -33°C)	18.6	12.7 (-33°C) 10.6 (45°C)	2.8 (-33°C)[1] 3.4 (45°C)[1]	80	100	Compliant with regulation	~90	~90
Methanol (CH_3OH) (65°C)	19.9	14.9	2.4	10	90–97	30–50	11	90
LPG (liquid, -42°C)	46.0	26.7	1.3[2]	50	90–100	10–15	13–18	90
LNG (liquid, -162°C)	50.0	21.2	1.7[2]	300	90–99	20–30	24	90
LEG (liquid, -89°C)	47.5	25.8	1.4[2]	380	90–97	30–50	15	90
MGO	42.7	35.7	1.0	7–8				
Hydrogen (H_2) (liquid, -253°C)	120	8.5	4.2					

1) The relative fuel tank size for ammonia has been provided for both cooled (-33°C) and pressurised tanks (45°C)

2) Assuming fully refrigerated media

Table 1: Alternative fuel comparison

However, ammonia has the potential to become the sustainable future fuel choice, when it is produced using hydrogen obtained by using renewal energy sources, see Fig. 2.

Ammonia (or anhydrous ammonia) is a globally traded commodity. The annual global ammonia production is approximately 180 million tonnes, of which approximately 80% becomes feedstock for fertiliser production [3]. Therefore, transport and storage of ammonia from production facilities to end users have been going on for years.

3.2.1 Electrolysis of water

To produce sustainable green ammonia using hydrogen obtained by electrolysis of water ($2H_2O \rightarrow 2H_2 + O_2$), the electricity must be produced using only renewable energy sources.

3.2.2 Nitrogen separation from air

Separation of nitrogen from air for ammonia production takes place via various technologies depending on the required purity and amount of ammonia. In large-scale productions of nitrogen, air is liquefied and separated into its constituents.

However, when it comes to the ammonia synthesis, the Haber-Bosch process is still the industrially applied method.

3.3 Challenges and advantages of ammonia fuel

There are challenges but also advantages associated with storage, transport and combustion of ammonia governed by the physical and chemical properties [3], see also Table 1:

- NH_3 is carbon- and sulphur-free and gives a clean combustion with near-zero generation of CO_2 or SO_X
- The volumetric energy density of NH_3 is higher than for H_2
- NH_3 can be cracked to N_2 and H_2
- NH_3 is non-explosive unlike H_2
- The widespread use of ammonia in industrial processes and as an agricultural fertiliser means that it is already a commercially attractive product
- It is less expensive and less complex to transport and store than hydrogen and other fuels in need of cryogenic temperatures
- The low risk of ignition in an ambient atmosphere makes the storage of large quantities of ammonia safer than hydrogen in terms of fire safety.

The lower heating value (LHV) of approximately 18.6 MJ/kg for ammonia is comparable to methanol. The energy density per unit volume of ammonia (12.7 MJ/L) and the other alternative fuels, is lower than that of MGO (35 MJ/L). To carry the same energy content of ammonia relative to MGO will require an approximately 2.8 times larger volume if the ammonia tank is cooled.

Although ammonia has the potential to become the future fuel, it is a toxic substance that, regulation-wise, has

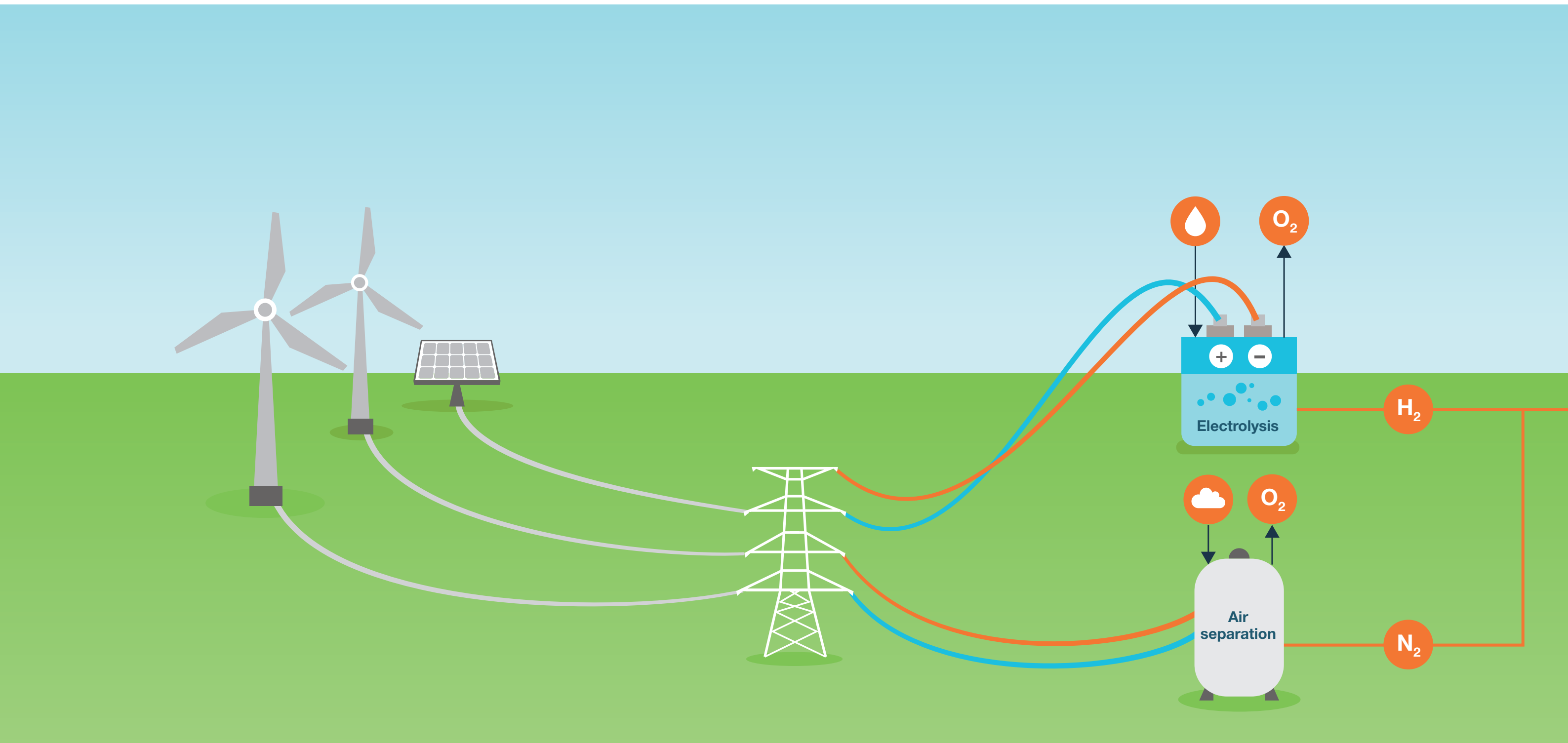


Fig. 2: Illustration of green ammonia production

not yet been released for use as a marine fuel.

3.4 Thermophysical properties of ammonia

Some of the physical properties of ammonia differ significantly from those of other fuels typically used for marine propulsion (see Table 1). These differences will dictate both the combustion system and the performance layout of an ammonia two-stroke engine.

Even though ammonia has a lower LHV than most other standard fuels, the low stoichiometric air-fuel ratio compensates for this, resulting in a comparable in-cylinder energy content. In this context, ammonia is similar to methanol. Ammonia as a fuel has a low flame speed compared to the other common fuels. This leads to a slower combustion process, which can reduce the efficiency.

Ammonia has a high autoignition temperature and a high heat of vaporisation, which acts to cool the in-cylinder charge. These combined effects can make the Diesel-type compression ignition of directly injected liquid ammonia challenging.

Ammonia also has an unusually high minimum ignition energy, which can be challenging for igniting a premixed ammonia/air mixture with an ignition system. However, these properties also have some positive aspects. These include a high resistance to knocking (indicated by the research octane number (RON)), which enables high compression ratios in engines using premixed combustion, increasing the efficiency.

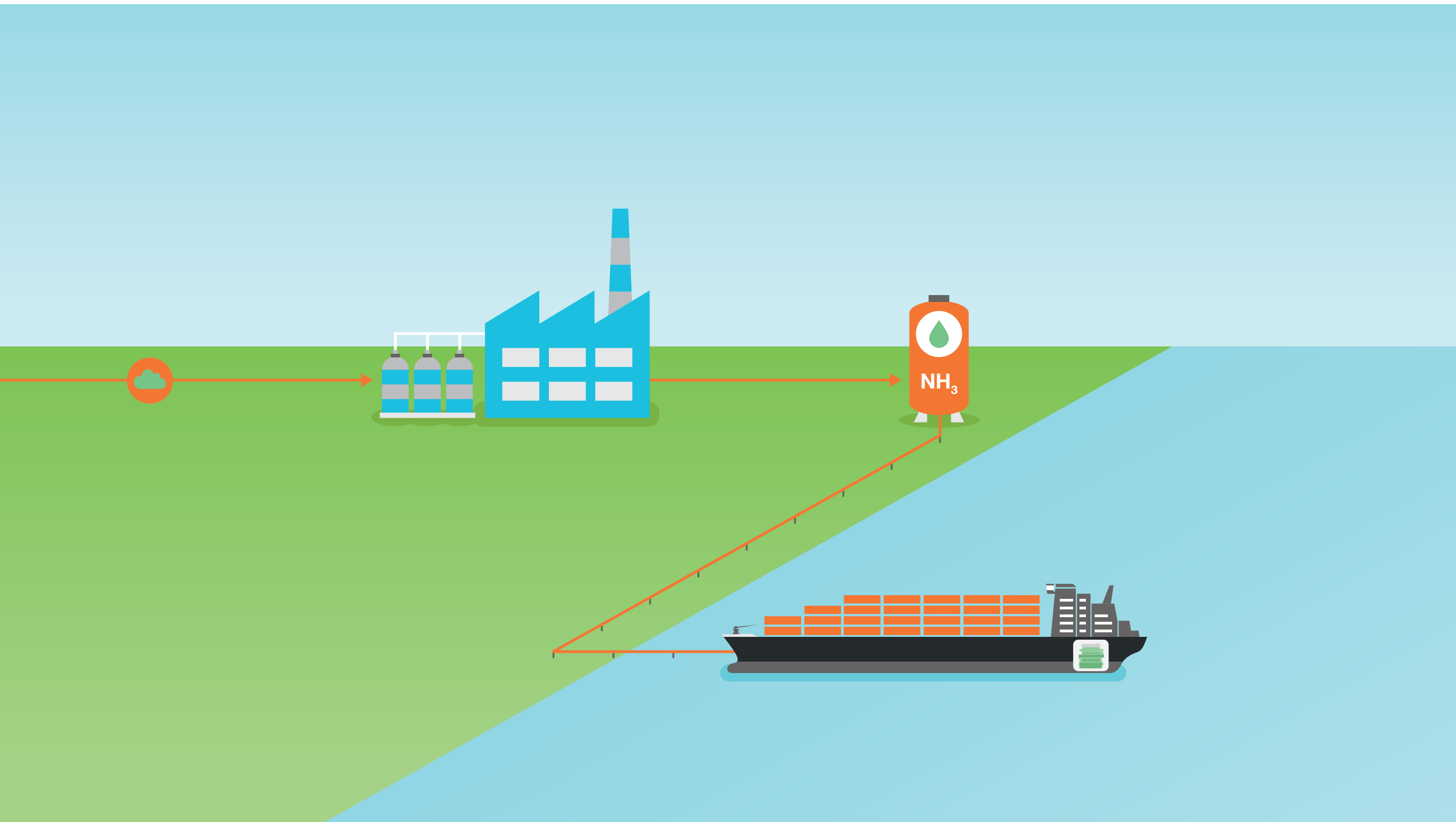
3.4.1 Handling characteristics of ammonia

The physical properties for storage and fuel distribution are similar to those of liquefied petroleum gas (LPG).

From a handling perspective, the most important aspect of ammonia is its high acute toxicity, which will have consequences for the design of storage, supply, engine, and after-treatment systems.

Despite the high toxicity, methods to safely handle ammonia have also been developed in other industrial applications – such as refrigeration. Ammonia has been stored and transported in tanks under modest pressure similar to LPG, and bulk transport of ammonia on board large chemical tankers is done using established technology. It is a common global commodity, which means that the handling and shipping infrastructure is readily available.

Because of the low reactivity, the hazards of accidental combustion or explosions are much lower than for other fuel gases and liquids. Despite the high toxicity to humans, a slip of ammonia to the environment, even in large amounts, leaves no significant long-term effects. Due to the high volatility in the gas phase, large solubility in water, and rather high chemical reactivity in water, it is readily diluted and disintegrated in the environment.



3.5 Trends in marine fuels

As phrased by Thomas S Hansen, Head of Promotion & Customer Support at MAN Energy Solutions: “No one can afford to go green alone“.

Introduction of regulation initiatives will be one of the cornerstones of the transition. To incentivise the industry to invest in equipment for future fuels, regulation initiatives governed by subsidies, CO_2 or GHG taxes have to be introduced.

The general public opinion is that the global warming challenge needs to be addressed and that the maritime industry must contribute to the CO_2 emission reduction. Today, the maritime industry accounts for approximately 3% of the global human-caused CO_2 emission. The existing fleet consumes close to 300 million tonnes of fuel oil annually. However, it also plays a fundamental role in the global economy, transporting more than 80% of the world’s total trade volume [3].

3.5.1 Prediction of the future fuel

It is difficult, if not impossible, to predict which fuels will carry off the title as future fuels. Since the future costs of different fuels is hard to predict, the shipowners want to be prepared. They are aware that the transition requires new fuels instead of the fuels we know today. The shipowners face a complex puzzle in the light of carbon-free or carbon-neutral fuel prices several times higher than the fuel oil prices today, and the fact that fuel often makes up the largest operational costs for vessels.

3.5.2 Regulation initiatives

For future CO_2-emission-free fuels to become attractive, the fuel prices, when considering all costs/incentives, must be comparable with traditional fuel prices. If achieved by a CO_2/GHG regulation as mentioned, the period for engine conversion to a future fuel can be short once the regulation becomes effective, and the implications to shipowners and yards must not be underestimated.

The question remains whether a part of the existing fleet will be CO_2/GHG regulated even stricter than required by the energy-efficiency design index (EEDI) or the energy-efficiency operational indicator (EEOI), or if regulations will apply only to new vessels from a certain date [4]. Based on the assumption that CO_2/GHG regulations will become effective within the next few years, a regulation of both existing and new vessels might be expected. Not to the same extent, but in a way that allows the environment the impeding benefit from the CO_2 emission reduction and at the same time avoids distorting the industry.

When looking at the market, we have picked up a distinct preference for ammonia compared to hydrogen. The explosion risk is one argument, but the discussion more often concerns the actual handling of hydrogen and the cost of handling it ashore and on board. Another important aspect is the high energy consumption required to liquefy hydrogen at -253°C, a more efficient approach is to use the hydrogen gas in the production of ammonia, which liquefies at -33°C. Handling of hydrogen is complicated and expensive compared to the ammonia solution. Engineering a practical solution for handling hydrogen that can be adapted to a typical two-stroke engine room is not without its hurdles. Still, many projects are ongoing and continuously increasing in number. The projects concern the development of production facilities, logistics, propulsion plant engines, and fuel supply systems (FSS) to handle ammonia.

The early, considerable, and increasing interest in using ammonia as a fuel made it part of the zero-emission strategy of MAN Energy Solutions to investigate and provide technology that utilises ammonia as fuel.

3.5.3 Ammonia fuel mixture

Today, many of the vessels delivered are ready for later dual-fuel adaption, as the engine builders are ready or working on being ready to retrofit their engine design accordingly.

The shipping industry has updated its GHG emission reduction targets to 20% reduction by 2030, and 70% by 2040, aiming for net-zero emissions by around 2050. The adoption of alternative fuels is emphasised, with a goal to account for at least 5% of the energy use by 2030. Expectations for fossil fuels to remain in the maritime industry for many years to come are lower based on the new MEPC80 regulations.

This possibility will lower the risk related to investing in a ship operating on ammonia, since conventional ammonia is a commercial commodity traded in large quantities.

4. In the process of developing the first two-stroke, dual-fuelled engine for ammonia

As Fig. 3 shows, one of the characteristics describing the two-stroke engine portfolio of MAN Energy Solutions is the fuel diversity. Since the beginning, the development of the MAN B&W two-stroke engine has been adapted to combust diverse fuel types.

In 2019, the journey towards a two-stroke engine operating on ammonia began, as illustrated in Fig. 4.

We started a pre-study of the fuel supply and injection concept and conducted several hazard identification, and hazard and operability studies (hazid/hazop) together with classification societies, shipowners, yards and system suppliers.

Presently, we are working on verifying the development concept of the injection system and the engine design in general. We finalised the development process of the ammonia engine in 2021 and the commercial design verification is scheduled for 2023. At the same time, we have been able to confirm the R&D potential of ammonia as a fuel during July 2023, when the first combustion confirmations tests were obtained at the test facility Research Centre Copenhagen (RCC) of MAN Energy Solutions [5].

When the engine design is released, the first engine can be prepared for test bed. The ammonia development project reaches a major milestone when the first ammonia engine is installed in a vessel during the first six months of 2024.

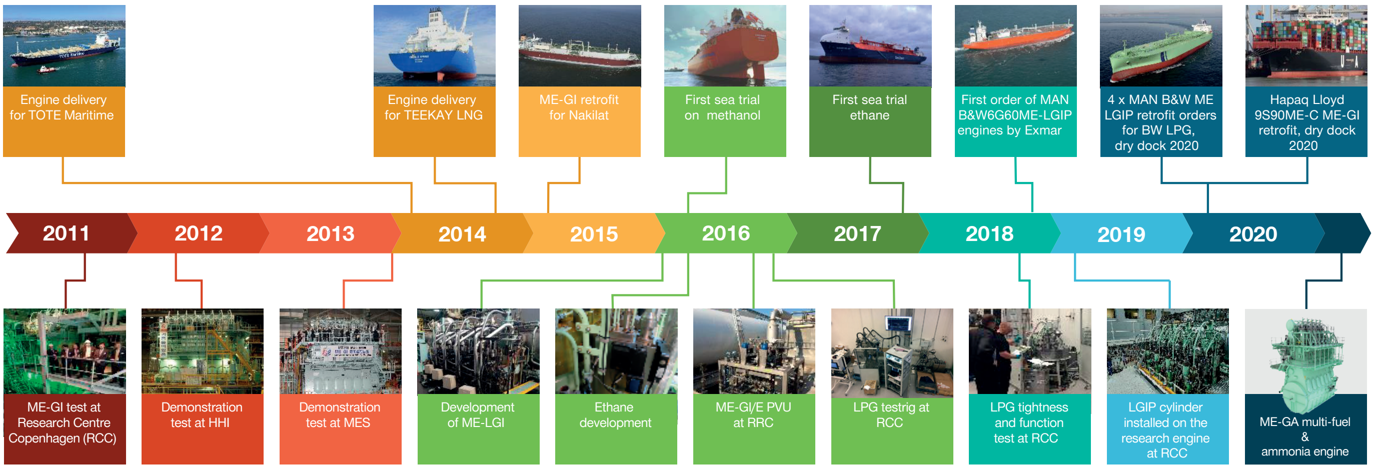


Fig. 3: Fuel diversity and engine types

2019 – Pre-study

- ✓ NH_3 combustibility investigation.

2020 – Project kick-off

- ✓ 4T50ME-X test engine received as platform for the ammonia engine development.
- ✓ HAZID workshop on engine concept.
- ✓ Combustion chamber 1st evaluation.

2021 – Engine concept R&D

- ✓ Engine basic concept defined based on R&D and simulations.
- ✓ Ammonia fuel supply & auxiliary systems specified.

2022 – Engine combustion and emission

- ✓ Ammonia fuel supply & auxiliary systems established in Research Centre Copenhagen (RCC).
- ✓ 1 cylinder engine and auxiliary system preparation at RCC.

2023 – Full scale engine test

- ✓ 1st bunkering of ammonia at RCC.
- ✓ 1st engine confirmation at RCC.
- – Full scale design work.
- – Specification of emission after-treatment.

2024 – 1st engine delivery to yard

- – Full scale engine test at RCC evaluated for 1st commercial design.
- – 1st ammonia fueled engine delivered to yard.

Fig. 4: Two-stroke ammonia engine development schedule

4.1 Engine foundation

When designing an engine governed by altered combustion physics due to the chemical composition of a new fuel, it requires thorough research of the influence on all conceivable engine design parameters to provide an efficient and safe engine and fuel supply system to the customers.

Currently, MAN Energy Solutions carries out research at the RCC and in different partnerships to assess the combustion and heat release characteristics of ammonia. The findings of the research will guide the development of the specific fuel injection properties and clarify the nature of two-stroke emissions, when operating on ammonia.

Ammonia is a toxic substance, and proper safety measures must be in place to safeguard the ship's crew and the surrounding environment. In addition to catering for these requirements, MAN Energy Solutions brings technology to the market that is engineered to adapt to the skills and work routines of the crew and the resources onboard. This is achieved without fundamentally changing the ship operation. An advantage of the ammonia-fuelled low-speed two-stroke engine is that it will not fundamentally change merchant shipbuilding or operation, and thus a simple and well-engineered solution is in place to cater for the requirements of this novel fuel.

The findings will also govern the FSS configuration. Part of the ongoing testing includes installation aspects and the FSS design will eventually be adapted to the outcome, we assume that the configuration for ammonia will inherit main features from the well-known LGP supply system for liquid injection.

As for the engine, development of an FSS calls for a safe and reliable design based on the outcome of hazid and hazop investigations. Currently, we have performed three hazid investigations observed by representatives from the classification societies, shipowners, yards and suppliers of components for the FSS.

In principle, the main differences between the fuel characteristics governing the ME-LGIP and the ammonia engine designs are related to heating values, the foul odour, and the corrosive nature of ammonia:

- lower heating values (LHV) of the fuels:
  - 46.0 MJ/kg for propane (LPG)
  - 18.6 MJ/kg for ammonia
- ammonia is corrosive to copper, copper alloys, alloys with a nickel concentration larger than 6%, and plastic

The ideal solution is to reuse part of the dual-fuel LPG injection system on the ammonia engine and part of the LPG fuel supply system from tank to engine [6].

4.2 Fuel supply system considerations

Fig. 5 and the following sections highlight the main principles of the fuel supply system for the ammonia engine and dual-fuel operation.

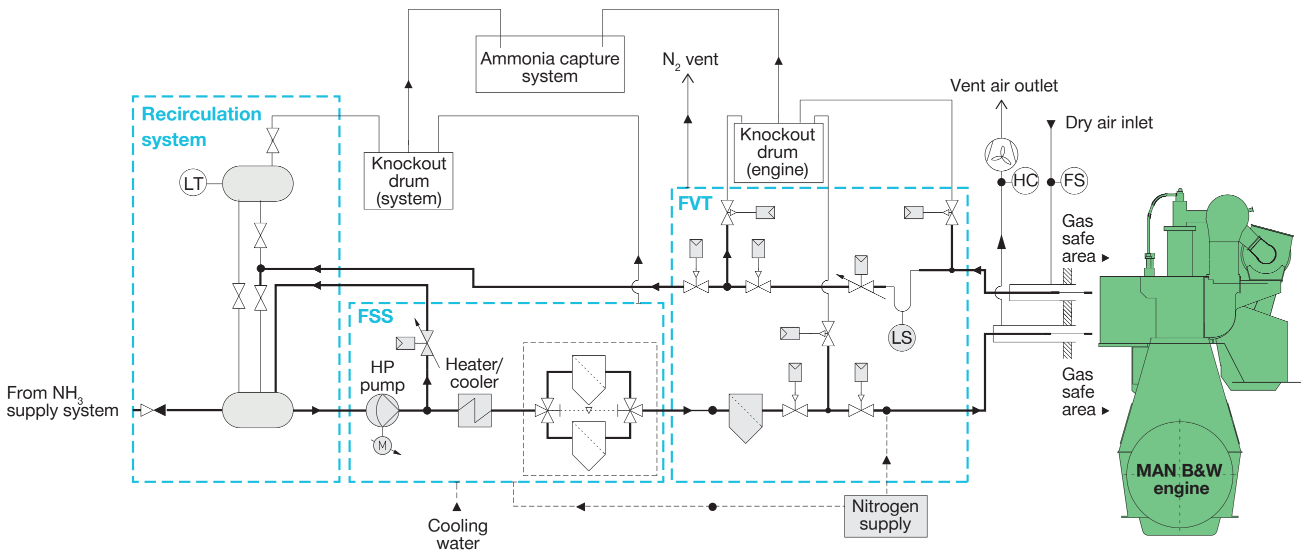


Fig. 5 Principles of the ammonia supply system showing main components

4.2.1 Principles of dual-fuel operation

During dual-fuel operation, the ammonia fuel supply to the engine comes from the storage tanks via the fuel supply system. To maintain the required fuel conditions at the engine, a small portion of the ammonia fuel continuously recirculates to the FSS via the recirculation system.
When the engine is not in dual-fuel mode, the double block-and-bleed arrangements of the FVT depressurise and completely isolate ammonia fuel systems inside the engine room from ammonia fuel supply and return systems. Before every start, the systems are pressurised with nitrogen to verify the tightness of the system.

When dual-fuel operation stops, the nitrogen pressure pushes back the ammonia fuel from the engine to the recirculation system. When the purging sequence is complete, the FVT will once again ensure the isolation of engine room systems from supply and return systems.

Throughout the entire operation, the double-walled ventilation system from existing MAN Energy Solutions dual-fuel engines detects any ammonia fuel leakage and directs it away from the engine room to a separate ammonia trapping system.

4.2.2 Recirculation system

The recirculated ammonia fuel will heat up in the engine during operation. To avoid two-phase conditions, a certain amount of ammonia fuel is recirculated to a dedicated recirculation line. The same recirculation line recovers the ammonia fuel from the engine whenever dual-fuel operation is stopped.

The recirculated fuel may contain traces of sealing oil from the injection valves. The recirculation line eliminates the risk of contaminating fuel storage tanks with oil. The recirculation line also separates and bleeds off nitrogen from the recovered ammonia fuel.

4.2.3 Fuel supply system

The FSS contains the equipment necessary to ensure that ammonia fuel is delivered to the engine at the required temperature, pressure and quality. In most cases, the FSS has a high-pressure pump, a heater, filters, valves, and control systems to maintain the ammonia fuel pressure and temperature at varying engine consumptions.

4.2.4 Fuel valve train

The fuel valve train (FVT) is the interface between the engine and auxiliary systems. The purpose of the FVT is to ensure a safe isolation of the engine during shutdown and maintenance, and to provide a nitrogen-purging functionality. The engine software control system actively monitors and controls the valves in the FVT. This functionality ensures a safe environment on the engine after shutdown.

4.2.5 Nitrogen system

Nitrogen must be available for purging the engine after dual-fuel operation, for gas freeing prior to maintenance and for tightness testing after maintenance. The capacity of the nitrogen system must be large enough to deliver a certain flow at a pressure higher than the service tank pressure. The flow required depends on the engine size.

4.2.6 Double-walled ventilation system

To maintain a safe engine room, it is vital to detect any leakages from the ammonia fuel system and direct these to a safe location. This has led to the double-walled design of ammonia fuel systems and piping inside the engine room. A constant flow of ventilation air is kept in the outer pipe in accordance with IMO requirements. The system is already part of other MAN B&W dual-fuel engine designs.

4.2.7 Ammonia capture system

Ammonia systems must be designed with an ammonia capture system (ACS) to prevent release of ammonia to the surroundings. The system consists of a knockout drum where the ammonia pressure will be released, see Fig. 5. Flash evaporation results in ammonia in liquid and vapour phases in the drum. The liquid phase is pushed back to the nitrogen separator, and ammonia in the vapour phase is captured in several columns filled with water. The amount of ammonia emission is controlled by the total water volume in the columns. During operation of the ACS, part of the water is drained off and replaced by freshwater.

4.2.8 Safety and control systems

The engine control system used for an ammonia engine is based on the system used for previous dual-fuel engines such as ME-GI (natural gas) and ME-LGIP (LPG). However, most similarities are found with the ME-LGIM (methanol) system.

The control and safety strategies used for methanol and ammonia are largely unchanged since the demands are quite similar. Both media are toxic to humans and pose a significant fire hazard if they enter the engine room.

The double-walled piping is continuously monitored to detect fuel leakages during engine operation. A positive detection leads to a controlled stop of ammonia operation on the engine while the piping containing ammonia is purged clean using nitrogen, and any further leakage is prevented. Note that a leakage takes place from the inner to the outer pipe and not to the engine room. This additional barrier keeps the ship and crew safe at all times.

4.3 Emission reduction technologies

It is expected, that the raw engine NO_X emission level of a two-stroke engine running on ammonia will be at a level comparable to a conventional low-speed diesel engine. However, the pathway of NO_X production during combustion is quite different from the conventional engine, and hence also the sensitivity to changes in engine performance.

Obviously, ammonia will only be an environmentally viable fuel if emissions known from a conventional engine are not merely replaced with other types of harmful emissions. Naturally, it is an important part of MAN Energy Solutions development efforts to ensure that only very low levels of any problematic emission escape from the ammonia engine, and that the new fuel will not create a new problem for the shipping industry to consider.

4.3.1 Selective catalytic reduction technology

To reduce emissions of nitrogen oxides (NO and NO_2, commonly referred to as NO_X) and to fulfil the regionally different emission regulations, engines from MAN Energy Solutions have been equipped with, for example, advanced selective catalytic reduction (SCR) technology. The SCR system using ammonia was introduced in the 1990s in four bulk carriers. Pending the outcome of the first engine test results, an increase in SCR volume and ammonia consumption may be necessary to achieve compliance in Tier III mode.

The SCR technology is an after-treatment process, where NO_X formed during the combustion is removed from the exhaust gas in a catalytic reduction.

Normally, the ammonia (reducing agent) required is added by injecting a urea solution ($CH_4N_2O + H_2O$) into the exhaust gas, however, ammonia can be injected as the catalytic agent instead of urea. One of the benefits of this is that an ammonia-fuelled vessel already carries ammonia. The consumption of ammonia for the SCR system will be very small compared to the ammonia fuel consumption.

Fig. 6 outlines the principle of selective catalytic reduction of the NO_X content in the exhaust gas.

In the catalytic reaction, NH_3 and NO_X are converted to diatomic nitrogen (N_2) and water (H_2O):

$$4NO + 4NH_3 + O_2 \rightarrow 4N_2 + 6H_2O$$
$$6NO_2 + 8NH_3 \rightarrow 7N_2 + 12H_2O$$

By ensuring a complete combustion, the emission of unburned NH_3 (ammonia slip) and the formation of nitrous oxide (N_2O) will be minimised.

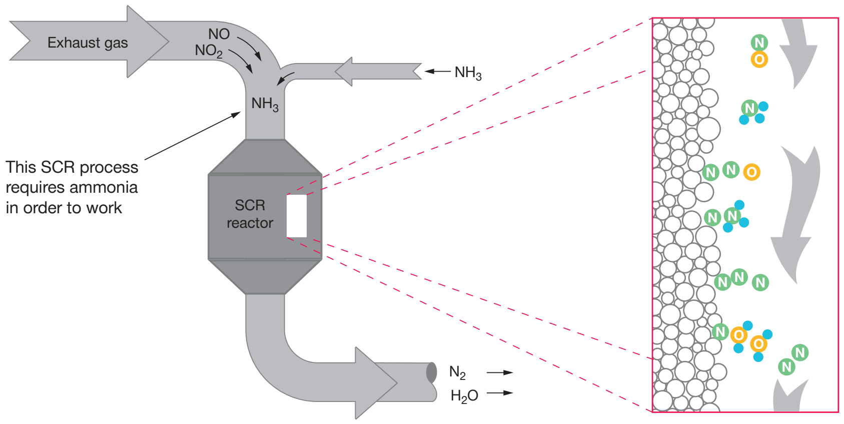


Fig. 6: The selective catalytic reduction process

5. Summary and outlook

Decarbonisation is a central and highly integrated part of developing sustainable technologies and solutions at MAN Energy Solutions.

Ammonia is used as an energy carrier of sustainable hydrogen and it is intrinsically carbon free. MAN Energy Solutions develops a dual-fuel two-stroke engine operating on ammonia. The technology developed aims for 90% decarbonisation of the ship powertrain in a tank-to-wake sense, while maintaining high power, energy density and efficiency, and low emissions.

However, as decarbonisation remains a global endeavour and one of the largest transitions within the maritime world, it will require a united maritime industry to question and evaluate the entire supply chain.

The Innovation Fund Denmark supports the AEngine project with the aim to design and demonstrate an ammonia-based propulsion system. MAN Energy Solutions is the AEngine project coordinator and part of the cross-functional project team together with Eltronic FuelTech (fuel supply systems), Technical University of Denmark and the classification society DNV GL.

As an important step towards a carbon-neutral economy, MAN Energy Solutions has joined forces with important players on the market in the launch of the Maersk Mc-Kinney Moller Center for Zero Carbon Shipping in Copenhagen. The combined global and cross-disciplinary effort will take us one step closer to the research required to highlight decarbonisation pathways. Research, which can guide and accelerate the development of carefully selected decarbonising fuels.

Furthermore, the global teamwork will support the establishment of vital regulatory, financial and commercial means to enable the transformation.

The future will see cleaner fuels, and the two-stroke engine technology will likely remain the prime propulsion motor for deep-sea shipping. Our engine portfolio shows that the MAN B&W two-stroke engines combust various fuel types. MAN B&W ME-C engines are based on future-proof technology that already can be retrofitted to run on LNG, LPG, ethane, and methanol as the fuel. The development of an engine type for ammonia supplements our extensive dual-fuel portfolio with an engine that will meet future market demands for CO_2-neutral propulsion including retrofits.

The future installation of an ammonia-combusting engine can be adapted to the customer, for example as a dual-fuel, modular retrofit solution for existing electronically controlled engines, as an ammonia-ready engine, or from newbuilding.

MAN Energy Solutions works diligently towards offering retrofit conversions of existing two-stroke engines to ammonia, preferably accommodating the vessels' five-year docking schedules after Q1 2025.

The advanced research and development of MAN Energy Solutions supports the transition of the industry by delivering the technology that helps our customers bring emissions to regulatory compliance, and even all the way to net zero.

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7. Acronyms and abbreviations

CCS	Carbon capture and storage
EEDI	Energy efficiency design index
EEOI	Energy-efficiency operational indicator
EGR	Exhaust gas recirculation
FSS	Fuel supply system
FVT	Fuel valve train
GHG	Greenhouse gas
GI	Gas injection
GWP	Global warming potential
HC	Hydrocarbon
IMO	International Maritime Organization
LGI	Liquid gas injection
LGIM	Liquid gas injection methanol
LGIP	Liquid gas injection propane
LHV	Lower heating value
LNG	Liquefied natural gas
LPG	Liquefied petroleum gas
MGO	Marine gas oil
NG	Natural gas
RCC	Research Centre Copenhagen
SCR	Selective catalytic reduction
VLSFO	Very-low-sulphur fuel oil

MAN Energy Solutions
2450 Copenhagen SV, Denmark
P +45 33 85 11 00
F +45 33 85 10 30
info-cph@man-es.com
www.man-es.com

5510-0241-02ppr Oct 2023. Printed in Denmark