Engineering the future two-stroke green-ammonia engine

MAN Energy Solutions
Future in the making

Fuelling the future by natural power
MAN B&W engines powered by zero-carbon fuels

Future in the making

Contents

Green ammonia produced from renewable sources is a strong candidate to a future compliant fuel.

This paper describes the development, benefits and application of the future ammonia-propulsion solution which includes: the MAN B&W two-stroke engine designed to operate on ammonia, the LFSS, and even two-stroke ammonia-fuelled gensets.

Introduction

Considering that the goal of IMO is to reduce the total annual GHG emission by at least 50% by 2050 compared to 2008 and, eventually, fully eliminate harmful emissions, the global maritime industry has to look into carbon-free fuels like hydrogen and ammonia. For technical reasons neither hydrogen fuel cells nor batteries seem to be realistic fuel scenarios in a near future for trans-oceangoing vessels. Ammonia constitutes a disruptive energy storage solution that can be produced using existing synthesis methods and storage solutions, and therefore has the potential to enter the market relatively quickly.

Regulation-wise the limitation placed on CO_2 emissions was introduced via the energy efficiency design index (EEDI) adopted by IMO [1]. The EEDI can be lowered to comply with EEDI regulations, for example by burning low-carbon or zero-carbon fuels, which makes these obvious candidates to becoming the fuel of the future.

By nature, the low-carbon fuels natural gas (NG), liquefied petroleum gas (LPG) and methanol generate less CO_2 emission during combustion than fuel oils. However, ammonia being a zero-carbon and -sulphur fuel has been considered a potential fuel candidate for decades. Research and experiments very early demonstrated the use of ammonia in smaller compression and spark ignited engines and turbines. Research of the ammonia combustion process has been ongoing since the 1930s, albeit with periods of standstill, and the research activities intensified during the 1960s [2].

Ammonia is a synthetic product obtained from fossil fuels, biomass or renewable sources (wind, solar, hydro or thermal), and when generated by renewable sources, ammonia will have virtually no carbon footprint or emit any CO_2, SO_X, particulate matter or unburned hydrocarbons when combusted. There will be only a minor contribution from the injected pilot fuel, which has the purpose to ensure a timed and controlled combustion of ammonia. The potential of ammonia as a fuel for two-stroke engine propulsion is huge as it will bring fulfilment of emission regulations, it has a higher volumetric energy density than liquid hydrogen, and it is less expensive and complex to transport and store than for example hydrogen and other fuels in need of cryogenic temperatures. Another important difference compared to hydrogen is that ammonia is not explosive.

The two-stroke engine portfolio of MAN Energy Solutions shows a large fuel diversity, however, all engine types are based on the strong heritage from the electronically controlled ME engine. One of the most essential engine design parameters is the Diesel principle. It is the main reason that the engine readily combusts a large variety of fuels, including poorly ignitable and burning fuels, with no or limited decrease in efficiency, and with the same reliable performance and operating characteristics as the conventional two-stroke engine. The properties of the two-stroke engine makes it the most reliable and economic choice for propulsion of trans-oceangoing vessels, also in the future.

MAN Energy Solutions is committed to continuously optimise the environmental impact of our engines, as an example the development of the methane combusting engine started as early as 1993. The timeline in Fig. 1 reflects the fuel versatility and ability of MAN B&W engines to combust almost any fuel type.

This history will continue into the future, MAN Energy Solutions will aim at developing engines matching the marine market and the individual demands of the ship-owners. The range of different fuels of the future marine market will reflect in the engine development, regardless of whether it is LPG, bio-fuels or ammonia.

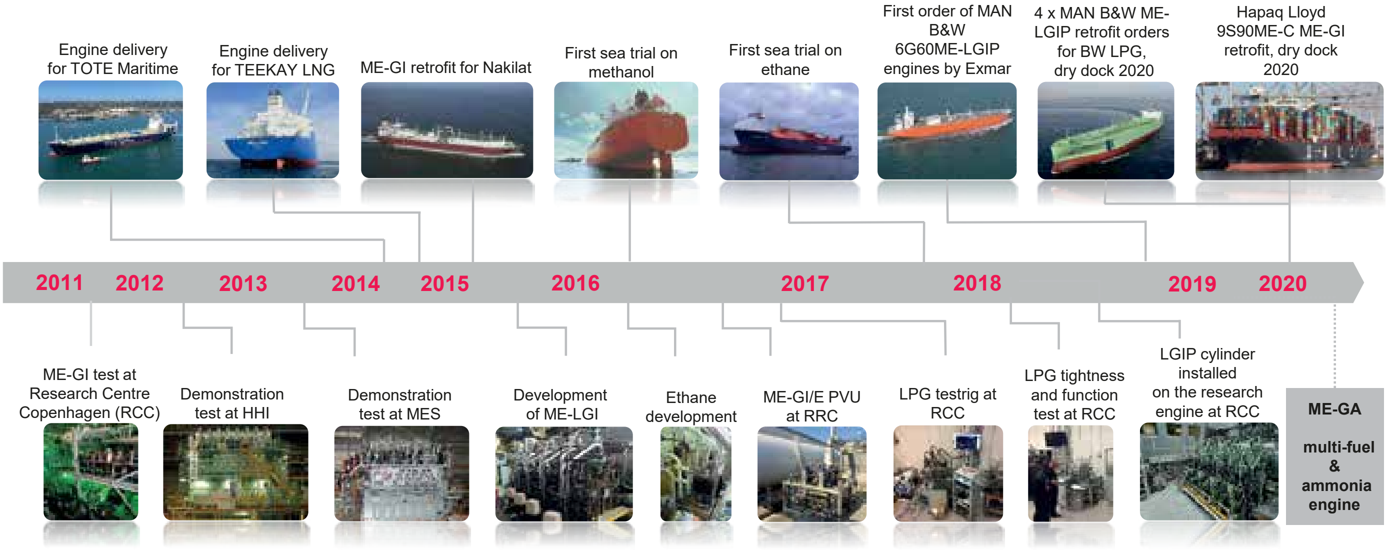


Fig. 1: The historical fuel timeline of MAN B&W two-stroke engines

Properties and combustion of ammonia

Ammonia is a synthetic product obtained from fossil fuels, biomass or renewable sources such as wind, solar, hydro or thermal, where the electricity can be stored as chemical energy in the ammonia molecule.

Physical and chemical properties of ammonia

In chemical data sheets, ammonia, with the formula NH_3, is described as a colourless inorganic compound composed of nitrogen and hydrogen molecules. The most important properties of ammonia, methane, methanol, ethanol, LPG and hydrogen related to combustion are shown in Table 1 for comparison.

Early ammonia became one of the most widely produced and transported bulk-manufactured chemicals. For example it was used in the production of ammonia-based agricultural fertilisers [2]. This makes the ammonia synthesis one of the most important processes in the chemical industry. It was commercialised at BASF over a century ago by Carl Bosch based on the fundamental and ground-breaking work of the German chemist Fritz Haber. He was awarded the Nobel Prize in 1919 and the pioneering work of both researchers gave name to the ammonia production process, the Haber-Bosch process.

The ammonia synthesis is described by the stoichiometric equation, which seems surprisingly simple: $N_2 + 3H_2 \rightarrow 2NH_3$. However, exploiting and optimising the mechanism behind has, for example for production reasons, occupied researchers for many years producing great results awarded with Nobel prizes [3, 4].

MAN PtX and production of ammonia

When producing green ammonia from renewable sources, the electricity is converted into the non-electrical form of energy. An excess production of electricity generated by renewable sources during peak production are at times sold with a financial loss without the possibility for storage [4].

Table 1

Energy storage type	Supply energy	Energy density	Required tank volume	Supply pressure	Injection pressure	Emission reduction compared to HFO Tier II			
	MJ/kg	MJ/L	m^3 *1	bar	bar	%	%	%	%
HFO	40.5	35	1,000	7-8	950	SO_X	NO_X	CO_2	PM
Liquefied natural gas (LNG -162°C)	50	22	1,590	300 methane 380 ethane	300 methane 380 ethane	90-99 90-97	20-30 30-50	24 15	90 90
LPG (including Propane / Butane)	42	26	1,346	50	600-700	90-100	10-15	13-18	90
Methanol	19.9	15	2,333	10	500	90-95	30-50	5	90
Ethanol	26	21	1,750	10	500				
Ammonia* (liquid -33°C)	18.6	12.7	2,755	70	600-700	90-95	Tier	95	90
Hydrogen (liquid -253°C)	120	8.5	4,117						
Marine battery market leader, Corvus, battery rack	0.29	0.33	106,060						
Tesla model 3 battery Cell 2170 *2	0.8	2.5	14,000						

Table 1: Physical and chemical fuel properties related to combustion in two-stroke engines, where *1 is based on a 1000 m^3 HFO tank, the additional space required for insulation is not included in the table. All pressure values are for high-pressure injection and *2 the values for the Tesla battery do not contain the energy/mass needed for cooling/safety/classification

Furthermore, storing renewable energy as ammonia has the advantage that when a shortage of electricity occurs on the grid, ammonia can be cracked to hydrogen for usage in fuel cells [5].

To exemplify the energy potential provided by solar radiation impinging on the earth, consider the energy available from the daily average irradiation of a 100 x 100 km^2 area in Australia which is: 24 MJ/m^2/day = 278 W/m^2. This amounts to 2,780 GW for the mentioned area. Calculating the electrical power, this corresponds to 550 GW electrical power when assuming a solar cell efficiency of 0.2. For comparison, the daily power consumption on a randomly chosen day in Denmark is 4.5 GW [6].

However, currently the large-scale ammonia production uses mainly fossil fuels, where hydrogen is sourced from hydrocarbons obtained from steam reforming of methane (CH_4). To produce green ammonia by electrolysis of water ($2H_2O \rightarrow 2H_2 + O_2$), the electricity must be produced using only renewable energy sources. A concept which is already part of the core technology of the MAN Energy Solutions Power to X (PtX) solution depicted in Fig. 3.

Power-to-X denotes the energy transformation from electricity to carbon-neutral synthetic fuels (gas or liquid) which can be stored and later used, like green ammonia.

Nitrogen for ammonia production can be separated from air by 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 [5].

Research on the ammonia synthesis remains a hot topic, and an article published in Scientific Reports in 2012, where they report one-step synthesis of ammonia from air and water at room temperature and one atmosphere [3], describes the advancement of the technology behind. The result is that the high pressure and temperature

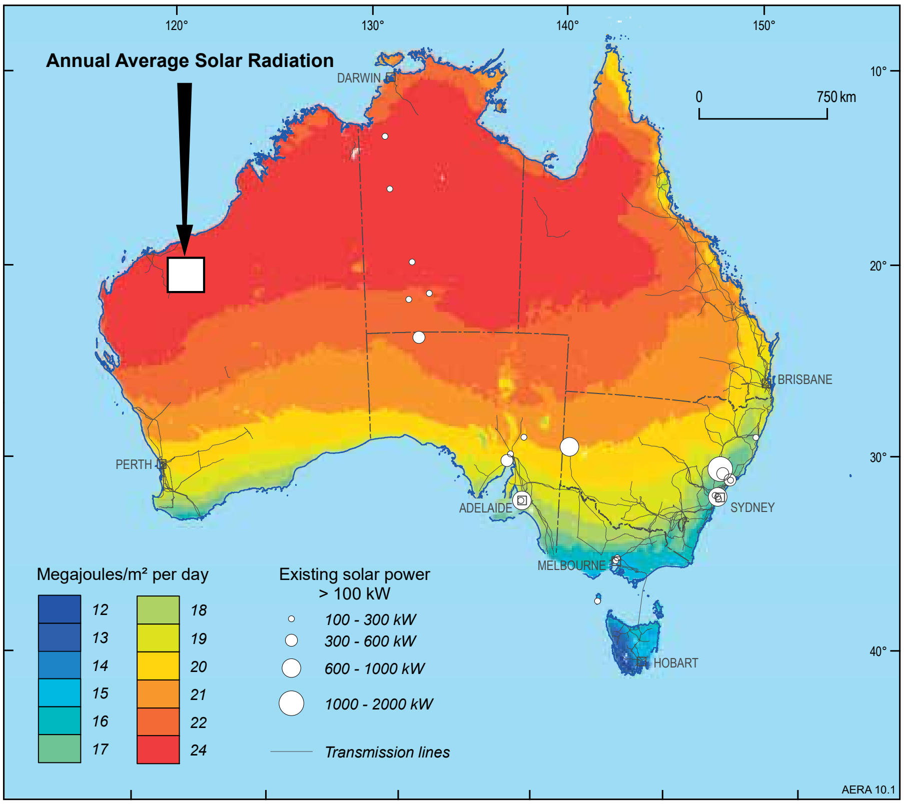


Fig. 2: The daily average solar radiation in Australia from 1 August 2018 to 31 July 2019 was 24 MJ/m^2 in the area on the map [5] (Source: Bureau of Meteorology 2009; Geoscience Australia)

Fig. 3: Production of green NH_3 by harvesting energy from renewable sources and using it to produce H_2 from water via electrolysis and N_2 via liquefaction of air

normally required for the Haber-Bosch process to take place is avoided. In general, a great deal of the ongoing research is devoted to optimising the catalyst needed in the synthesis.

To sum up, the storage, transport and combustion of ammonia has a number of benefits stemming from the favourable physical and chemical properties of ammonia, NH_3 [2], see also Table 1:

- NH_3 is carbon- and sulphur-free and gives a clean combustion without generation of CO_2 or SO_X.
- The volumetric energy density of NH_3 is higher than for H_2.
- It is easily liquefied by compression to approximately eight bar. Pressurised storage (at a pressure above 8.6 bar at the ambient temperature 20°C) keeps ammonia in the liquid phase but it is commonly stored at approximately 17 bar to keep it in the liquid phase if the ambient temperature increases.
- NH_3 can easily be cracked to N_2 and H_2.
- There is a low risk of fire since a relatively specific ratio of NH_3 and air (15-25%) is required to sustain a combustion.
- NH_3 is non-explosive unlike H_2
- The widespread use of ammonia in industrial processes as an agricultural fertilizer and immediate power generation makes it a commercially attractive product.
- The easier transportation and storage of NH_3 compared to H_2 for which it is highly complex.
- An established and reliable infrastructure already exists for storage and distribution of ammonia.

Ammonia combustion engine – in a historic perspective

The potential of ammonia as a fuel was demonstrated as early as 1822 where ammonia was used to fuel a gas locomotive. Due to political reasons and funding at that time, steam was preferred and only few other attempts to use ammonia as a fuel were made. In 1943, liquid ammonia was used as fuel for buses in Belgium to keep public transportation in operation during World War II.

Research very early demonstrated the use of ammonia in smaller compression and spark ignited engines and later on in turbines. Research of the ammonia combustion process has been ongoing since the 1930s, albeit with periods of standstill, and the research activities intensified during the 1960s [2]. Through the years, extensive research has been conducted to expose the detailed fundamental properties of ammonia combustion, for example the detailed reactions, combustion stability, prediction and investigation of NO_X and NO_2 emission, ignition improvers and flame speed enhancers. However, during the last decade research has again gained the interest of many large research groups across the globe to come up with a solution to feeding a growing world population, i.e. the need for ammonia-based fertilisers, and the current production of ammonia seen in the light of decarbonisation [3].

The challenges related to ammonia combustion as concluded from research on combustion in smaller engines and turbines are the high NO_X generation, low flammability and low radiation intensity. However, the benefits of the Diesel principle and the high combustion temperature of approximately 1300°C are a very stable and robust combustion. The typical dimensions and rpm of an MAN B&W two-stroke engine allow the time for a complete combustion of the fuel to take place. The high injection pressure enabling a nearly complete distribution of fuel in the combustion chamber also ensures this. Furthermore, the injection of pilot oil enables control of the combustion process and provides measures like pulsed or extended ignition. The possibility also exists to achieve the optimal progress of the combustion by changing the pilot oil type, for example to dimethyl ether (DME) or H_2.

History and the timeline in Fig. 1 shows that the future most optimal and environmentally friendly engine propulsion system could indeed be ammonia-fuelled.

The two-stroke dual-fuelled ammonia combusting engine

The two-stroke ammonia concept is an add-on to the ME engine similar to the previous engine concepts for liquid gas injection propane, ME-LGIP (LPG) [7] and liquid gas injection methanol, ME-LGIM.

MAN B&W ME-GI and LGI engines have gained a considerable number of service hours powering vessels at sea, and the ME-LGIP engine introduced in 2019 is already in the order book. The ME-LGIM engine type has been in service for some time and has achieved 50,000 running hours on methanol. The LGIM concept is used as basis for the LGIP engine. The development of the LGIM engine also dealt with some of the challenges related to ammonia, e.g. corrosion, toxicity and low flammability. The same engine concept, already verified at sea, will constitute the core of the ammonia-combusting engine. There will be no visible differences between an ammonia and an ME-LGIP/LGIM engine.

Fig. 4 shows the ME-LGIP cylinder cover with LPG injection valves and valve control block, the same system will be used for the ammonia engine.

Currently, research is carried out together with a university in Japan to assess the combustion and heat release characteristics of ammonia. The results of this research will guide the development of the specific fuel injection properties. However, it has been established that the supply pressure will be approximately 70 bar and the injection pressure 600 to 700 bar.

In general, the exothermic combustion of ammonia giving nitrogen and water is described by the reaction: $4NH_3 + 3O_2 \rightarrow 2N_2 + 6H_2O + \text{heat}$

NO_X emissions can be reduced with the exhaust gas after-treatment technology, the selective catalytic reduction (SCR) system. The reducing agent, NH_3, is injected into the exhaust gas resulting in only nitrogen and water as waste:
$4NO + 4NH_3 + O_2 \rightarrow 4N_2 + 6H_2O$
$6NO_2 + 8NH_3 \rightarrow 7N_2 + 12H_2O$

The SCR principle is outlined in Fig. 5.

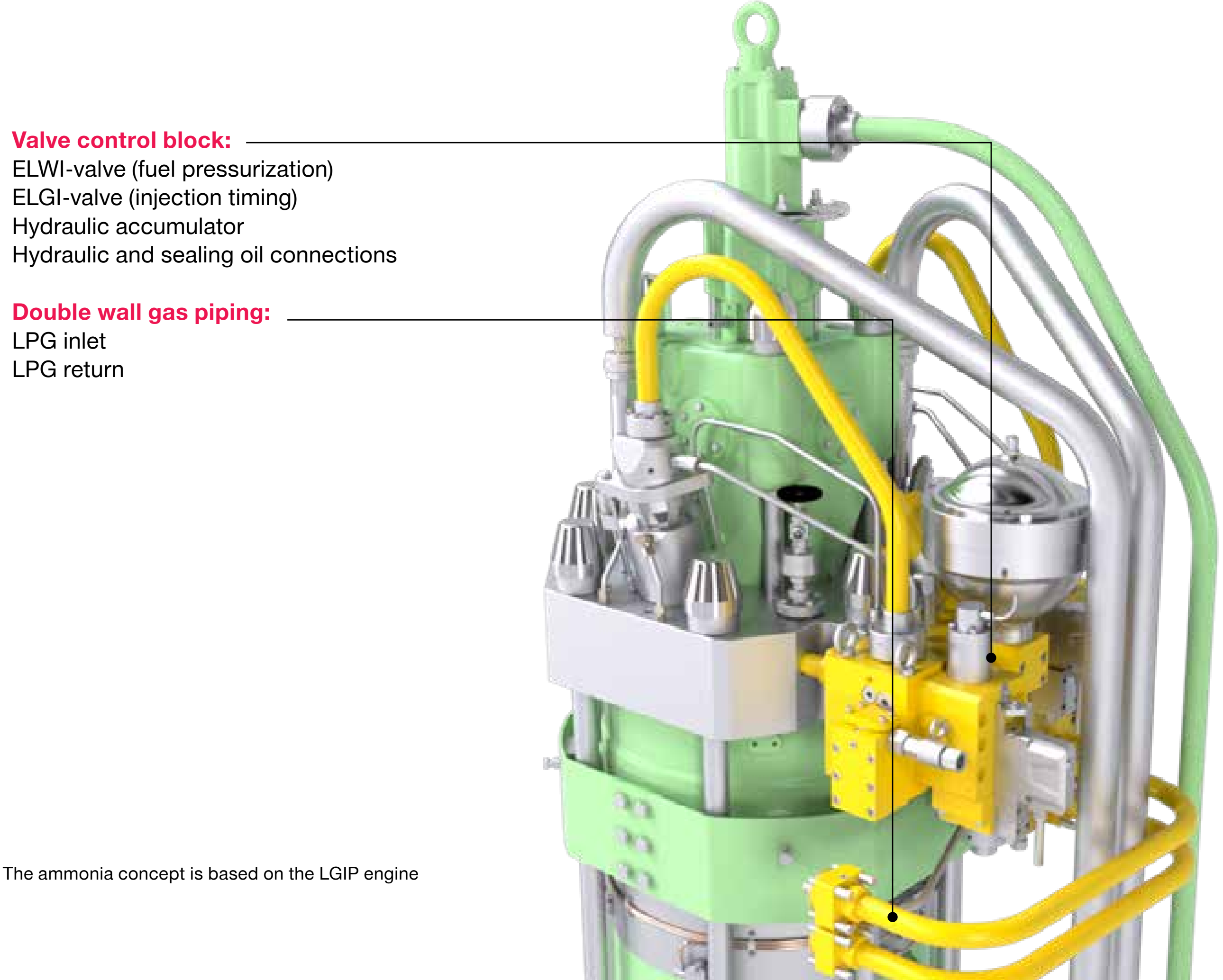


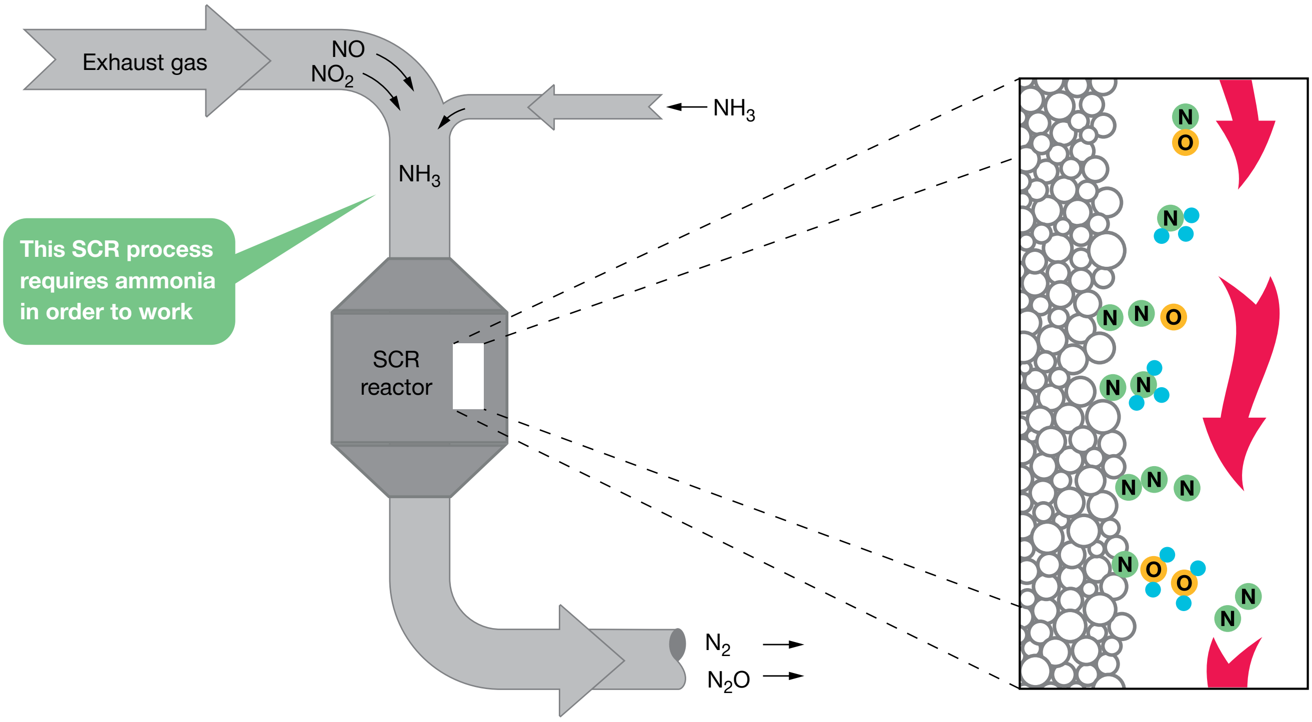
Fig. 4: The ammonia concept is based on the LGIP engine

One of the benefits is that the vessel is already carrying the reducing agent, ammonia.

Reduction of NO_X formation can also be done by applying the internal engine process, exhaust gas recirculation (EGR). The EGR system reduces the formation of NO_X by controlling the combustion. In short, the system controls and reduces the peak temperature of the combustion and the NO_X formation by redirecting part of the exhaust gas (CO_2) to the scavenge air receiver (O_2) after a cooling and cleaning process. Since the exhaust gas only contains a negligible particle matter content, it will be a small and compact EGR design, which does not require a lot of space on-board. When combusting ammonia, the EGR system can be designed without the water treatment system for cleaning and neutralisation of the water with sodium hydroxide.

Since ammonia is a toxic chemical, the proper safety precautions must be observed. However, on many vessels ammonia has been handled routinely as part of the SCR system. Note, that when comparing with previous applications of ammonia on shore, there are system differences. One is the already well-known double-walled design of fuel pipes. The fuel pipes on the ammonia engine are double walled and the design of the outer shielding pipe prevents gas outflow to machinery spaces in the event of a leakage or rupture of the inner gas pipe. A separate mechanical ventilation system with a capacity of 30 air changes per hour vents the intervening gas pipe space, including the space around valves, flanges, etc. Any leaking gas is led to the ventilated part of the pipe system, where hydrocarbon sensors will detect it. Another difference is the advanced safety and control system of the engine, which ensures a safe operation on all our gas engines.

During some aspects of maintenance, where there is a potential risk of minute amounts of ammonia after purging, the crew must carry out maintenance wearing gas masks. This has been normal procedure when performing maintenance on refrigerating plants for years.



This SCR process requires ammonia in order to work

Fig. 5: The selective catalytic reduction process

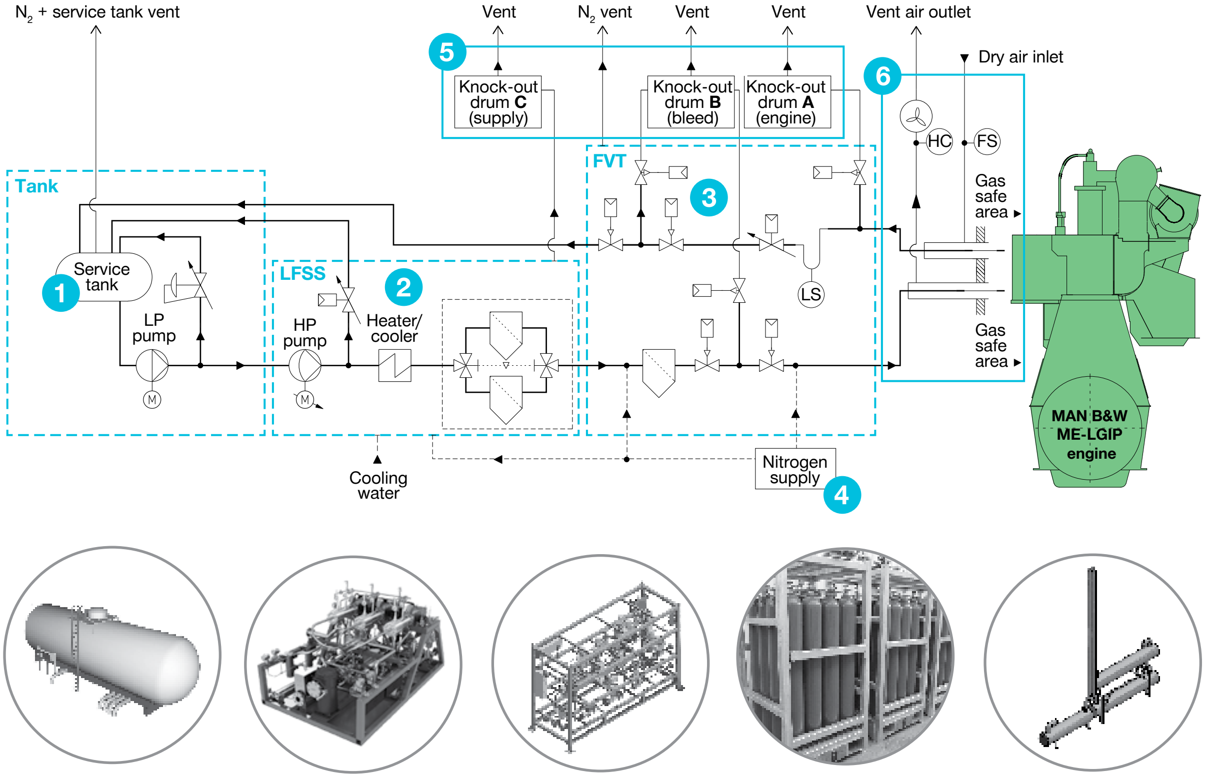
Ammonia fuel supply systems

The underlying basis for the ammonia low-flashpoint fuel supply system (LFSS) is the LGP LFSS, because it can be redesigned to accommodate the physical properties governing ammonia storage and injection.

Typically, vessels transport LPG (consists of light hydrocarbons, mostly propane, butane and propylene) in Type C pressurised tanks at approximately 18 bar. Ammonia can be stored on vessels under the same conditions as LPG. The ammonia tank volume will be twice that of LPG due to the lower energy density, see Table 1. Ammonia will be in the liquid phase at a pressure above 8.6 bar and an ambient temperature of 20°C. However, ammonia is commonly stored at approximately 17 bar to keep it in the liquid phase when the ambient temperature increases. In the future, an engine running on LPG could be converted to an ammonia combusting engine.

Since ammonia is corrosive to copper, copper alloys, alloys with a nickel concentration larger than 6% and plastic, these materials must be avoided in the fuel system. The sealing rings for the ammonia engine will be of the Teflon type. As for the requirements to the nickel alloy, the nickel concentration must be kept below 6% to avoid the phenomenon of nickel crystalline corrosion, and the material strength of the alloy should be increased by for example heat treatment. This provides another option, namely that tanks used for storage of LNG with the same requirements can be used for storage of ammonia. This means that, when green ammonia becomes available in large quantities, it can replace LNG and the engine can be converted to ammonia operation.

Fig. 6 shows a complete LGIP fuel supply system with the components needed to supply LGIP to the MAN B&W ME-LGIP engine [7].



1. LPG service tank
2. Low-flashpoint fuel supply system
3. Fuel valve train
4. Nitrogen storage
5. Knock-out drums

Fig. 6: The ammonia LFSS will be a modified low-flashpoint supply system for LGIP engines [7]

In the ammonia fuel supply system, the ammonia returning from the two-stroke engine will be collected in a smaller separate tank in order not to contaminate the ammonia content of the service tank with sealing oil. The sealing oil system provides lubrication of fuel injection components and prevents LPG contamination of the system oil.

An emergency vent of NH_3 can be carried out by one of the following principles: dilute the concentration of NH_3 to below 10 ppm, collect NH_3, or extend the vent mast to a safe height. If the combustion of ammonia gives rise to obnoxious smells from the funnel, the option exists to heat up the exhaust gas to obtain a higher buoyancy of the exhaust gas. A solution that is used for LPG combusting engines as well.

As an example, Fig. 7 shows the ship design and LFSS of an LR1 tanker, the main components will be identical for an ammonia-based propulsion system [7]. Only the volume of the ammonia tanks will be twice that of the LPG tanks.

The global infrastructure for transport of ammonia is already widely expanded. The most obvious candidates for ammonia-based propulsion systems on a short-term scale are ammonia or LPG tankers. These tankers can transport LPG as well as ammonia thanks to the similarity of the storage requirements, e.g. temperature and pressure. The large number of MAN B&W engines powering these vessels can be retrofitted to combust the fuels LPG or eventually, ammonia. It will even be possible to order an ammonia-ready engine design for LPG combustion.

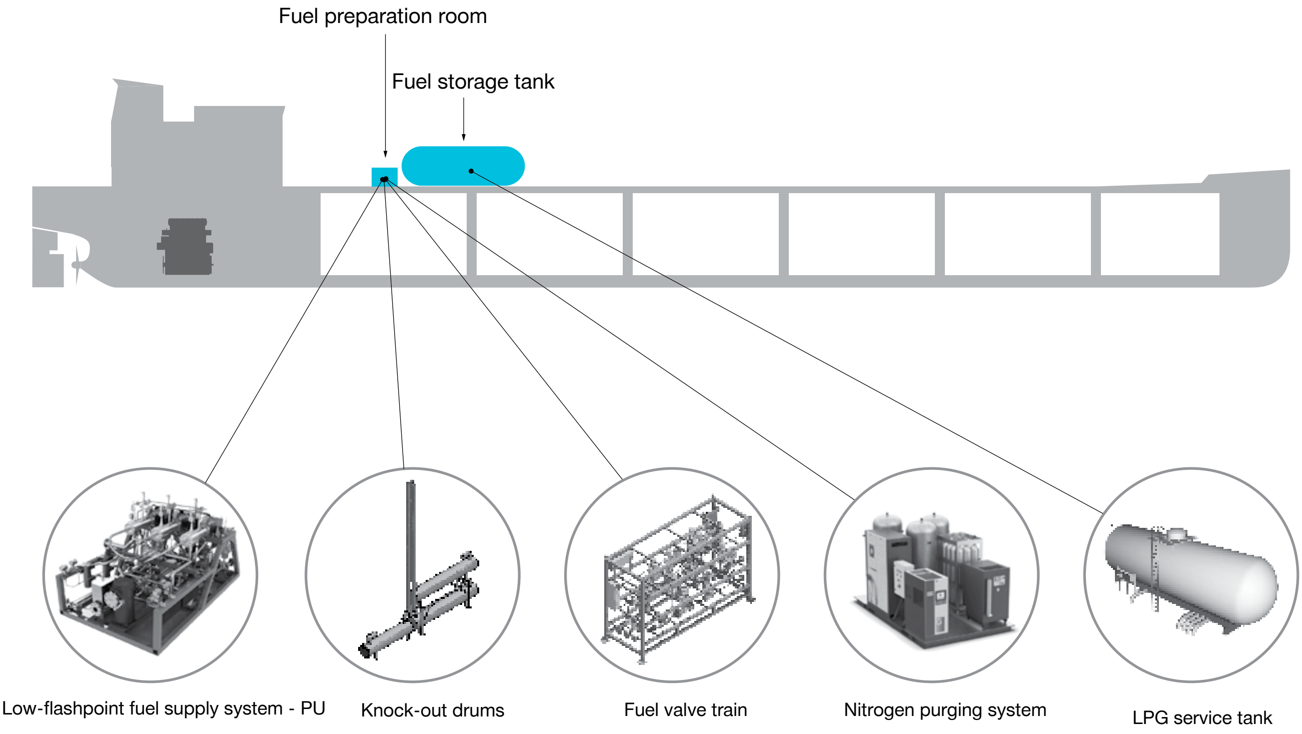


Fig. 7: Ship design and LFSS for an LR1 tanker – the same design will be applied for an ammonia-propelled vessel [7]

The future green-ammonia vessel solution

In a world demanding fuel flexibility and fuel efficiency, MAN Energy Solutions looks not only at the main engine but also at the power generation on board. The power supply on board is normally delivered by gensets, however, we foresee a potential in applying MAN B&W two-stroke engines for power generation as well.

This is technically possible, as the capacities and technical requirements for MAN B&W engines are identical whether they are running as main engines or as two-stroke gensets. This solution will enable only one fuel gas supply system (FGSS) and one fuel oil supply system for both main engine and generating sets. This can take the uni-concept to the next stage in terms of common fuel oil systems, common cooling water systems and a common starting air system. Moreover, the capacities and requirements are well known to a wide range of component suppliers and shipyards worldwide, this is a benefit from an installation and operating point of view.

The ship design has to be changed to accommodate MAN B&W two-stroke gensets, and for this purpose we are in close coordination with leading ship designers and shipyards with the aim to provide this solution to the shipping industry.

There are various solutions to evaluate from both an economic and an installation perspective. One solution is a directly coupled generator with fixed rpm, a solution already used for power generation on land with a 2 GW MAN B&W engine. The solution can be optimised from a design point of view when MAN Energy Solutions can provide engines with custom tuning and speed de-rating for a given ship. The fuel efficiency of this solution is unrivalled. Speed de-rating allows a change of the generator diameter while maintaining a sufficient safety margin in over-speed situations.

In such a context, the MAN B&W engine is very dynamic. The second option is a directly coupled variable-rpm generator with frequency conversion. So far, results have indicated an efficiency loss of approximately 4% due to the frequency conversion. The solution is interesting from a part load perspective and due to the anticipated lower price of the system. A system that comprises variable-rpm generator, frequency conversion and connection to the grid. The challenge is the pricing of the frequency conversion system and the possible need for battery capacities to safeguard the MAN B&W engine in over-speed situations and to optimise ship grid stability.

With a design basis that is approximately 95% identical with that of the main propulsion engine, it makes sense to explore the genset solution further. Installation perspectives, fuel gas selection and market interest will determine the implementation rate of two-stroke gensets. MAN Energy Solutions keeps an open mind, and we want to be part of working out solutions that are relevant not only to shipowners and ship operators, but also to shipyards and the future shipping market.

Conclusion

Ammonia is inherently carbon- and sulphur-free and when used as fuel in MAN B&W two-stroke engines, the emission of CO_2, SO_X, unburned hydrocarbons and particulate matter will be virtually eliminated. Seen in the light of the low cost and low complexity of storage, and the already existing ammonia production facilities and infrastructure, ammonia is an obvious future fuel.

History has shown us that ammonia works as an engine fuel. Our engine portfolio shows that the MAN B&W two-stroke engines can combust literally any fuel type. The development time of an ammonia engine is expected to be two to four years. The future installation of an ammonia-combusting engine can be done in more ways: for example as a dual-fuel retrofit solution for existing electronically controlled engines, as an ammonia-ready engine, or from newbuilding.

Obvious first movers for ammonia propulsion are the LPG carriers, which also from time to time carries an ammonia cargo, and ammonia carriers, which already have the necessary auxiliary equipment and expertise on board.

The technology is here, we are ready, when the marine market is ready. When the production of green methanol, ammonia, LNG and biofuels can meet the quantities required in the maritime industry for two-stroke propulsion, we can deliver the engine.

Our existing solutions to increase efficiency can be installed, and if at some point green ammonia prices escalate, the WHR solution, for example, can be installed to increase efficiency.

MAN Energy Solutions aims at providing optimal and green vessel solutions. By adopting the concept of two-stroke gensets, the efficiency and simplicity of the combined propulsion and generating solution will be unsurpassed.

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Acronyms and abbreviations

EEDI	Energy efficiency design index
EGR	Exhaust gas recirculation
FGSS	Fuel gas supply system
IMO	International marine organisation
LFSS	Low-flashpoint fuel supply system
LGIM	Liquid gas injection methanol
LGIP	Liquid gas injection propane (LPG)
LPG	Liquefied petroleum gas
NG	Natural gas
RCC	Research centre copenhagen
SCR	Selective catalytic reduction

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5510-0241-00
Nov 2019 Printed in Denmark