Ammonia-fuelled MAN B&W 2-Stroke Dual-fuel Engines*

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1. Why Consider Ammonia as Marine Fuel?

The aim of this paper is to share our knowledge of ammonia (NH_3) as a potential fuel for marine engines. We are technology providers with a well-founded opinion on the future fuel. We know that various fuels are already in use, but these are still produced from fossil fuels and are not sustainable when looking at the environment and the internationally agreed limitations on global warming.

Many different assumptions prevail on the maritime market and it is difficult, if not impossible, to predict which fuel will carry off the title as the future fuel. The market is screaming for facts and easy solutions to enable shipowners and investors to order new vessels and engines prepared for the future to come.

Several countries have already specified CO_2 targets and funds support projects considering future fuel scenarios. These include scenarios with equipment prepared from newbuilding or equipment prepared for later retrofit to another fuel like on some vessels. However, there is no final solution and one prediction can be as good as the other.

That said, the general public opinion is that the global warming challenge must be taken seriously this time and that the maritime industry must contribute to the CO_2 emission reduction. Today, the maritime industry accounts for 3-4% of the global human-caused CO_2 emission. An understanding

reflected in discussions and statements from shipowners. They face a choice of fuel and engine type with potentially devastating economic consequences in a competitive maritime market.

The fact that many different fuels categorise as potential future fuels demonstrates the general market interest. In addition, the realisation has dawned upon players in the market that no one can afford to be green alone. Regulation initiatives governed by subsidies, CO_2 or greenhouse gas (GHG) taxes need to be introduced to incentivise the industry to invest in equipment for future fuels. Nevertheless, shipowners understand that they must use new fuels instead of the fuels we know today. The prices on carbon-free or carbon-neutral fuels are several times higher than the prices of the fuel oil available today.

Fossil fuels will remain in the maritime industry for many years to come, especially during the transient period from 2020 through 2030. The maritime industry has to find the future fuel. Today, the existing fleet consumes close to 300 million tonnes of fuel oil annually. It constitutes an enormous inertia, which cannot change direction easily.

The question also arises 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 [1]. However, 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,

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but in a way that does not distort the industry and at the same time allows the environment the impending benefit from the CO₂ emission reduction.

The fuel cost is by far the largest operational cost for vessels today. And as the development of the future cost of different fuels is hard to predict, the shipowners want to be prepared. Many of the vessels delivered today are therefore prepared for later dual-fuel adaption, as the engine builders are ready or working on being ready to retrofit their engine design accordingly.

Different interest groups promote their favourite future fuel like, for example, methanol, eLNG, biofuel, NH₃, H₂, etc. These interest groups add knowledge about availability, logistics and pricing to the discussions on future fuels. This knowledge not only contributes to fulfilling the targets for non-carbon and GHG emissions, but also enables the possibility to choose between multiple fuel types. When looking at the market, shipowners highly favour NH₃ compared to H₂. The explosion risk is one argument, but the discussion more often concerns the actual handling of H₂ and the cost of handling ashore and onboard. The handling of H₂ will be complicated and expensive compared to the NH₃ solution. 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 (LFSS) to handle NH₃.

To make the future CO₂-emission-free fuels attractive, the fuel prices must be comparable with today's fuel prices. If achieved by a CO₂/GHG regulation as mentioned, the time for engine conversion to a future fuel can be short once the regulation becomes effective, and that must not be underestimated. The early, considerable, and increasing interest in using ammonia as a fuel made it part of the zero-emission strategy of MAN ES to investigate and provide technology that utilises ammonia as fuel. Table 1 shows the properties of several alternative fuels.

2. Ammonia Compliance and Availability

2.1 Environmentally safe

Ammonia, one nitrogen atom bonded to three hydrogen atoms, is a synthetic product produced from renewable sources, biomass or fossil fuels. Green ammonia produced from renewable sources has virtually no carbon footprint and emits no CO₂, SO_x, particulate matter (PM) or unburned hydrocarbons (HC) during combustion. These environmentally beneficial properties show the huge potential of ammonia as a fuel.

Ammonia as a fuel enables compliance with emission regulations and, in addition, offers a number of other beneficial properties:

- the volumetric energy density of ammonia is ~12.7 MJ/m³ and that of hydrogen is ~8 MJ/m³

Table 1 Properties of alternative fuels (1): Given a 1000 m³ tank for MGO. Additional space for insulation is not included. All pressure values given presuppose the high-pressure Diesel injection principle.

Energy storage type	Specific energy [MJ/kg]	Energy density [MJ/L]	Required tank volume [m ³] ⁽¹⁾	Supply pressure [bar]	Estimated PtX efficiency	Injection pressure [bar]	Emission reduction compared to HFO Tier II			
MGO	42,7	35	1000	7-8		950	SO _x	NO _x	CO ₂	PM
Liquefied natural gas (liquid, -162°C)	50	22	1590	300 methane	0,56	300 methane	90-99%	20-30%	24%	90%
				380 ethane		380 ethane	90-97%	30-50%	15%	90%
LPG (including propane/butane)	42	26	1346	50		600-700	90-100%	10-15%	13-18%	90%
Methanol	19.9	15	2333	10	0,54	500	90-97%	30-50%	5-7%	90%
Ammonia (liquid, -33°C)	18,6	12,7	2755	70	0,65	600-700	100%	Compliant with regulation	>95%	>90%
Hydrogen (liquid, -253°C)	120	8.5	4117		0,68					

(liquid)

- 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 ambient atmosphere makes the storage of large quantities of ammonia safer than hydrogen in terms of fire safety.

Hydrogen liquefies when cooled to temperatures below -253°C , LNG at -163°C , by contrast, ammonia liquefies 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 commonly stored at approximately 17 bar.

2.2 Availability

Already a familiar commodity, ammonia is a fuel alternative attracting interest in the industry. The production of black ammonia constitutes one of the largest productions of inorganic chemicals. Ammonia is widely used as an agricultural fertiliser and in the production of plastics, fibres, explosives, nitric acid and as intermediates for dyes and pharmaceuticals.

Although it is in the nature of things that ammonia emits no CO_2 , as it contains no carbon atoms, large-scale production of ammonia is based on a century-old recipe, and it often uses natural gas as feedstock. However, research on the ammonia synthesis is a hot topic.

During the last decade, ammonia research has gained momentum. Research groups across the globe are dedicated to develop a solution that can feed a growing world population and meet the need for ammonia-based fertilisers. The production of food uses by far most of the fertilisers produced today, primarily from LNG and coal.

To produce green ammonia by electrolysis of water ($2\text{H}_2\text{O} \rightarrow 2\text{H}_2 + \text{O}_2$), the electricity must be produced using only renewable energy sources. Fig. 1 shows the concept, which is already part of the core technologies of MAN ES' Power to X (PtX) solution. PtX denotes the energy transformation from electricity to carbon-neutral synthetic fuels (gas or liquid) which can be stored and later used, like green ammonia.

The ammonia molecule can be used as an energy storage solution. Since ammonia is produced and stored using existing synthesis methods and storage solutions, it has the potential to enter the market relatively quickly. Ammonia can also provide an alternative storage facility for hydrogen, a molecule that is difficult to transport.

An established and reliable infrastructure exists for storage and distribution of ammonia. Furthermore, synthetic fuels can use the same infrastructure as petroleum fuels, but ammonia has to be produced from renewable sources to qualify as green.

Fig. 1 PtX

3. The MAN B&W Engine Operating on Ammonia

3.1 A historic perspective on ammonia as a fuel

As early as 1822, ammonia was used to fuel a gas locomotive. However, only few other attempts to use ammonia as a fuel were made due to political reasons and funding of the time.

The use of ammonia in smaller compression and spark-ignited engines was demonstrated early. Research of the ammonia combustion process has been ongoing since the 1930s providing the detailed fundamental properties of ammonia combustion, for example, detailed reactions, combustion stability, prediction and investigation of NO_x and NO₂ emission.

3.2 The beneficial Diesel principle and combustion of ammonia

One of the characteristics describing the 2-Stroke engine portfolio of MAN ES is the fuel diversity. Another 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 2-Stroke engine.

The Diesel principle is the decisive design parameter and the main reason that 2-Stroke engines can combust various fuels and fuel qualities, including poorly ignitable and burning fuels.

The combustion of fuel in MAN B&W GI and LGI engines based on the Diesel principle is stable, robust, and takes place at a high temperature, approximately 1300°C. Compared to the other GI and LGI dual-fuel engines operating on methane, ethane, methanol and LPG, the challenge is that ignition of ammonia takes more energy due to the low flammability and low radiation intensity.

Ammonia is inherently carbon- and sulphur-free and when used as fuel in MAN B&W 2-Stroke engines, the emission of CO₂, SO_x, unburned HC and PM will be virtually eliminated. The exhaust gas emission will be monitored closely in the coming test. There is an expectation that the NO_x level will

increase compared to the fuel oil burning engine. A small increase in SCR volume and ammonia consumption will then be necessary to achieve compliance in Tier III mode. Ammonia can be used as the catalytic agent instead of urea. The SCR system using ammonia was introduced for the first time in the 1990s in four bulk carriers. By ensuring a complete combustion, the emission of unburned NH₃ (ammonia slip) and the formation of nitrous oxide (N₂O) are considered insignificant.

The Diesel principle gives complete control of the ignition timing, allowing the time for a complete combustion of the fuel to take place. The high injection pressure is a contributing factor since it enables a nearly complete distribution of fuel in the combustion chamber.

All things considered, we have a solid foundation for the engine development when looking at ammonia and the chemical composition. We expect to inject ammonia in liquid form into the engine. This will be finally confirmed when ammonia has been tested in our most recent research engine in Copenhagen. We will run the test similar to other dual-fuel tests with a complete engine monitoring setup to get information about the ignition properties of ammonia and the pilot oil requirements. Based on the information obtained, we will be ready to start the final design of the ammonia-burning engine.

3.3 Developing an ammonia engine

In 2019, 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 work on a verification of the development concept of the injection system design and the engine design in general. We will finish the development process in 2021.

The commercial design verification will be finalised in 2023. Next, the engine design will be released and an engine can be prepared for test bed. During the first six months of 2024, the first ammonia engine can be installed in a vessel.

3.4 The design sketch of the ammonia 2-Stroke engine

The ammonia engine design will resemble our propane engine (ME-LGIP) [2]. The final design may change based on the results of the upcoming testing on the research engine.

The main differences between the characteristics governing the ME-LGIP and the ammonia engine designs are:

- lower calorific values (LCV) of the fuels:
 - 46.4 MJ/ Kg for propane
 - 18.6 MJ/ Kg for ammonia
- ammonia is corrosive to copper, copper alloys, alloys with a nickel concentration larger than 6% and plastic
- propane and ammonia are both injected into the combustion chamber at 600–700 bar.

The ideal solution will reuse part of the LPG injection system on the engine and part of the FGSS from tank to engine. Some owners show great interest in an option that allows them to order an LPG engine that can later be retrofitted to operate on green ammonia when it is available and demanded due to emission regulations. However, the final testing of ammonia combustion in MAN ES research engines must confirm this.

3.5 The dual-fuel working principle

The MAN B&W ME-XXXX ammonia engine is designed for dual-fuel operation on low-flashpoint fuel ammonia and pilot oil, see Fig. 2.

Fig. 2 Dual-fuel principle

When the piston has compressed the scavenge air in the top of the liner, pilot oil is injected first and ammonia is then injected into the burning flame of the pilot fuel. This controls the timing and how the combustion process develops.

3.6 Fuel injection system design

In general, the ammonia injection part is designed as an add-on system to the ME engine, similar to the concept for ME-GI (LNG), LGIM (methanol) and ME-LGIP (LPG).

The main components of the system are injectors, gas control blocks, pipes and accumulators.

Fig. 3 shows the fuel booster injection valve for propane (FBIV-P) as representative of an ammonia injector.

Fig. 3 Fuel booster injection valve

The injector design has two main functions:

1. To pressurise or boost the fuel gas to the desired injection pressure
2. To ensure the correct timing and duration of the injection.

Fig. 4 shows the cylinder cover and the valve control block that houses an electronic window valve

(ELWI), an electronic gas injection valve (ELGI), a hydraulic accumulator, and connections for hydraulic oil and sealing oil.

Fig. 4 Engine top with valve control block and double-walled gas piping

The ELWI valve with a window function controls the fuel gas pressurisation and the ELGI valve controls the injection timing. Separate control units in the engine control system control the two valves, independently, to provide extra safety.

Low-pressure liquid fuel gas is supplied to the injectors, where high-pressure hydraulic oil boosts and increases the fuel gas pressure to the injection pressure.

Sealing oil separates the two systems to avoid contamination of the hydraulic oil with fuel gas. The sealing oil is lubricating oil from the 2-Stroke main engine. A small amount of sealing oil enters the fuel gas supply line, mixes with the fuel gas, and continues to the injectors.

The safety concept requires that the design of the fuel gas piping in the engine room is double-walled with a ventilated outer pipe. Any potential seal leakages are vented to the outer pipe to avoid the risk of a fuel gas leakage to the engine room. HC sensors monitor for any leakages and an alarm will sound if they detect a fuel gas leakage.

4. Auxiliary System Design

Fig. 5 shows a conceptual diagram of the ammonia supply system. The supply system contains a fuel supply system (LFSS), which provides the required fuel gas conditions at the injection valve. The main components of the system in Fig. 5 are:

1. Recirculation system (4.1)
2. LFSS (4.2)
3. Fuel valve train (FVT) (4.3)
4. Nitrogen system (4.4)
5. Double-walled ventilation system (4.5)
6. Ammonia capture system (4.6)

Fig. 5 Conceptual diagram of the ammonia supply system

The remaining part of this chapter describes the main components of the fuel supply system and the principles of dual-fuel operation.

4.1 Recirculation system

The recirculated fuel gas heats up in the engine during operation. To avoid two-phase conditions, a certain amount of the fuel gas is recirculated to a dedicated recirculation line. The same recirculation line recovers the fuel gas 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 fuel gas.

4.2 Fuel supply system

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

4.3 Fuel valve train

The FVT is the interface between the engine and the 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. This functionality ensures a safe environment on the engine after shutdown.

4.4 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.

If the vessel already has a nitrogen generator onboard, a nitrogen booster and cylinder bank can make up the required nitrogen setup. Alternatively, the nitrogen supply can come from a skid

containing nitrogen generation, booster and storage facilities.

4.5 Double-walled ventilation system

To maintain a safe engine room, it is vital to detect leakages from the fuel gas systems and direct these to a safe location. This has led to the double-walled design of fuel gas 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.

4.6 Ammonia capture system

The ammonia systems must be designed with an ammonia trapping system to minimise release of ammonia to the surroundings.

4.7 Principles of dual-fuel operation

When the engine is not in dual-fuel mode, the double block and bleed arrangements of the FVT depressurise and completely isolate the fuel gas systems inside the engine room from the fuel gas supply and return systems. Before every start, the systems are pressurised with nitrogen to verify the tightness of the system.

During dual-fuel operation, the fuel gas 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 fuel gas continuously recirculates to the LFSS via the recirculation system.

When dual-fuel operation stops, the nitrogen pressure pushes back the fuel gas 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 the supply and return systems.

Throughout the entire operation, the well-known double-walled ventilation system from existing MAN ES dual-fuel engines detects any fuel gas leakages and directs it away from the engine room to a separate ammonia trapping system.

5. Summary

MAN B&W ME-C engines are based on future-proof technology that we can retrofit to run on LNG, LPG, ethane and methanol as fuel. The development of an engine type for ammonia supplements MAN Energy Solutions extensive dual-fuel portfolio with an engine that inherently meets future market demands for CO₂-neutral propulsion.

MAN Energy Solutions works diligently towards offering retrofit conversions of existing 2-Stroke engines to ammonia, preferably accommodating the vessels' five-year docking schedules after Q1 2025.

References

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