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High efficiency ammonia combustion in the MAN B&W LGI-A marine two-stroke engine

Fuels - Alternative & New Fuels

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ABSTRACT

Transoceanic shipping needs to decarbonise in order to meet global greenhouse gas (GHG) reduction targets, as shipping accounts for around 3% of global GHG emissions. Ammonia is widely considered the fuel of choice for decarbonising the shipping industry. MAN Energy Solutions has risen to the decarbonisation challenge, and the MAN B&W LGI-A engine is now ready for commercial application over a range of ship types.

In this paper we will report performance and emission trends observed from single-cylinder, as well as from full engine R&D tests on the 4T50ME-X-LGIA research engine. We demonstrate that a high efficiency combustion process, with an ammonia energy fraction above 95% combined with very low laughing gas emissions, is possible in a full size two-stroke marine diesel engine. The ignition and combustion mode was also studied in detail using high-speed in-cylinder optical diagnostics.

Ammonia was directly injected at high pressure into the engine cylinder and ignited using a small diesel pilot flame. This resulted in a stable dual-fuel combustion process, with large robustness to varying operating conditions. GHG savings exceeding 90% at full load were possible, as laughing gas emissions as low as a few parts per million were recorded. An optimised NH3 injection system was developed, to enable low ammonia slip out of the engine. This ensures a high combustion efficiency, up to 99.7%, as well as an indicated efficiency matching that for operation on diesel fuel. NOx emissions were substantially lower compared to operation on diesel fuel. The low-speed two-stroke design thus appears well suited for operation on ammonia. The long residence times in combination with swirling in-cylinder flow allows for efficient burn-out of the ammonia, which has previously been considered a problem for ammonia as IC engine fuel.

1 INTRODUCTION

Climate change driven by anthropogenic emission of greenhouse gases, predominantly CO_2, is one of the largest challenges mankind has faced [1]. The projected continuous increase in global energy demand [2] makes the development of climate neutral energy production an urgent priority. Transoceanic shipping is the backbone of international trade, at the same time it is one of the largest individual contributors to greenhouse gas emissions [3]. The shipping industry currently accounts for around 3% of the global GHG emissions [4]. The international maritime organisation (IMO) recently set the target to reach net-zero GHG emissions by 2050 [5]. At present large ships employ large two-stroke diesel engines, due to their robustness, high efficiency and capability of direct propeller coupling [6]. Traditionally, these engines are operated on heavy fuel oil or distillate diesel oil, but over the last decade engines running on new marine fuels like natural gas and methanol have been developed [7,8,9]. Whereas transition to these fuels has a positive impact on the environment, it is only with the transition to carbon free fuels like NH_3 and H_2, or the use of carbon capture and storage, that full CO_2 neutrality will become a possibility [10,11].

Ammonia is widely considered to be the fuel of choice for green shipping in the future. It is safer to handle compared to hydrogen, due to its lower ignitability and flammability. It also allows more economical storing and logistics, due to its higher volumetric energy density under standard conditions [12,13,14]. There are challenges, however, with using ammonia as fuel since it has a poor flammability and low flame speed. This poses several technical challenges, such as achieving a stable ignition, allowing a high NH_3 energy fraction – as required to minimise the GHG impact, and reaching an efficient burn out of the fuel and thus achieving a high efficiency. Furthermore, ammonia combustion can generate high laughing-gas (nitrous oxide: N_2O) emissions, which quickly offset the greenhouse gas benefits [15]. In order to achieve a fast widespread uptake as a marine fuel, a combustion technology allowing ammonia to be burnt efficiently in an commercially established propulsion system needs to be developed. Challenges with introducing ammonia into the marine industry also include production, cost, availability, transport, storage, port logistics and safety. Whereas NH_3 is predominantly produced from natural gas today, it can also be produced from just air and water, using renewable electricity from wind, solar or hydro [10,11,12,16,17]. The current annual growth rate of renewable energy is around 10% [2]. This growth is projected to increase further, making it feasible to supply the marine market with affordable green ammonia in the future. The introduction of a greenhouse gas levy for shipping might also accelerate the transition to carbon free fuels [5]. More than 100 ports around the world are already equipped with ammonia trading facilities [18], which provides a good starting point for establishing a global NH_3 bunkering network. Due to its acute toxicity, the handling of ammonia on board a ship needs special attention. As ammonia is one of the most transported chemicals in the world and widely used in the agricultural and refrigeration industries, the infrastructure is already well established [13]. This includes safe and economical on-board storage and delivery, as well as safe handling procedures.

Over the last decade ammonia has been investigated as a fuel for a range of internal combustion (IC) engine sizes [19,20,21, 22,23,24,25,26]. In all these studies the cylinder volumes were 10 to 100 times smaller, and engine speeds at least 10 times higher, than that of the engine employed in this study. Marine two-stroke engines have several characteristics which can overcome the challenges previously encountered in smaller four-stroke engines, making them ideally suited for efficient NH_3 combustion. First of all, the large combustion chamber design results in a small surface to volume ratio. This in combination with the strongly swirling in-cylinder flow ensures that the directly injected ammonia as well as the ammonia flame are kept away from walls. Thus, heat losses and flame quenching leading to incomplete combustion are minimised. Strong swirl has previously been demonstrated to be advantageous for stabilising NH_3 flames also in gas turbines [27]. Secondly, the slow engine revolution speed leaves sufficient time to complete the slow ammonia combustion. Direct fuel injection and a diesel type combustion process, in combination with a large expansion ratio ensures a high thermodynamic cycle efficiency. The resulting stratification, with minimum pre-mixing, promotes a combustion process which minimises N_2O emissions. Finally, the use of a dual-fuel principle in which a small diesel pilot flame is used for ignition, ensures the high ignition energy and large ignition volume required for overcoming the poor NH_3 flammability and ensuring a self-sustaining NH_3 combustion process. The potential for operating a full-scale marine engine on NH_3 has recently been investigated in smaller test chambers and compression machines, with the main focus on ignition properties [28,29,30,31,32]. To this date, however, a full-scale demonstration of a large marine engine with a GHG saving potential fulfilling future emission targets has been missing.

Here we present an efficient and stable low-emission NH_3 engine process, based on an industrially relevant engine platform – which is technically feasible to implement in current ship designs. A GHG saving of above 90% at full load, compared to operation on diesel fuel, is demonstrated when running on ammonia. The high GHG saving results from very low N_2O emissions and a high NH_3 energy fraction. Combustion efficiencies as high as 99.7% were observed, resulting in low emissions of unburnt NH_3. Furthermore, NO_x emissions were observed to be lower than for conventional diesel operation.

2 4T50ME-X TEST ENGINE

The engine used to demonstrate the ammonia combustion concept, 4T50ME-X, is a four cylinder engine. The specifications are given in Table 1. The engine employs uniflow scavenging, with scavenging ports at the bottom of the engine cylinder, and a centrally placed hydraulically actuated and electronically controlled exhaust valve in the cylinder cover at the top of the cylinder. The turbo charger (ABB A170) was equipped with a variable turbine geometry (VTG) allowing for adjustment of the scavenge air pressure at any given load point.

Table 1. 4T50ME-X specifications

Cylinders	4
Bore	0.5 m
Stroke	2.2 m
Swept volume	0.43 m^3
Power	6.2 MW
Max speed	123 rpm
MEP	18.5 bar
Max pressure	190 bar

For the tests reported here cylinder four is converted to ammonia dual-fuel operation, see Fig. 1. The remaining cylinders are operated on diesel fuel and are tuned to achieve the desired test conditions for cylinder four. This allows for a wide range of conditions to be tested on cylinder four.

Figure 1. Photo of cylinder cover for ammonia tests mounted on the MAN B&W 4T50ME-X test engine in Copenhagen.

Two ammonia injectors were mounted on the test cylinder, see Fig. 2. The ammonia injection valve is of a booster valve type, where the ammonia is pressurised to the final injection pressure using a plunger. By varying the hydraulic oil activation pressure, the injection pressure can be adjusted. The injection pressure was increased from around 550 bar at low load to around 720 bar at full load. As the heating value and density of ammonia are lower than for diesel, the injector nozzle holes are larger for ammonia than for diesel, in order to achieve a similar injection duration. Details of the NH3 supply system are provided in a dedicated paper [33].

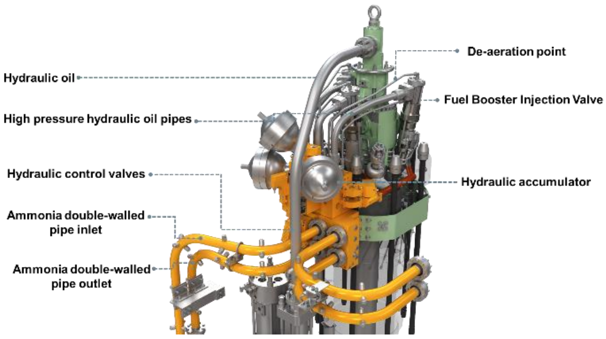

Figure 2. Cylinder cover for ammonia tests.

Component materials as well as the hydraulic sealing oil were carefully selected to secure ammonia compatibility. Several safety features were implemented to guarantee safe ammonia and engine handling during testing. Double walled piping, with dedicated venting, ensures that any ammonia leakage is rapidly detected and handled in a safe manner.

A gas sampling probe, positioned just after the exhaust valve of cylinder 4, was used to sample emissions from only the cylinder operating on ammonia. The sampling probe was connected to a low-pressure drum, via a controlled valve which was synchronised with the exhaust valve opening on cylinder 4, so as to only sample gas in motion. The exhaust gases were analysed using a combination of standard exhaust measurement equipment from Horiba and a Fourier transform infrared spectrometer (FTIR, MKS), used to measure NH_3, N_2O, NO and NO_2. Total engine out emissions from all four cylinders, sampled after the turbine, were also sampled and analysed according to normal operating procedures using the same analysers. Emissions of CO_2, O_2, CO, H_2O, THC (total hydrocarbons), N_2O, NO, NO_2, and NH_3 were continuously measured.

High-speed images were recorded using a CMOS camera (Photron SA-Z), with a resolution of 1024×1024 pixels and a maximum speed of 20000 frames/second at full resolution. A borescope was inserted into a diesel fuel injector port, which was fitted with a sapphire window [34]. The borescope allowed an optical view across the combustion chamber, covering most of the flame originating from the injection on the other side.

3 RESULTS

3.1 NH_3 engine operation

In the dual-fuel process employed here, the ammonia is injected directly into the cylinder at high pressure, as in a classical diesel process. It is then ignited close to piston top dead centre (TDC) by a separate small pilot injection of diesel fuel. For most tests presented here the energy content of this diesel pilot corresponds to 3%-6% of the total energy at full load. In Fig. 3 (a) and (b) the cylinder pressure and heat release rate (HRR) curves corresponding to 25%, 50%, 75% and 100% engine load, respectively, are shown. Typical cylinder pressure and HRR curves from a similar sized commercial engine operating on conventional marine diesel (c) and (d) and on methanol (e) and (f) are plotted for comparison.

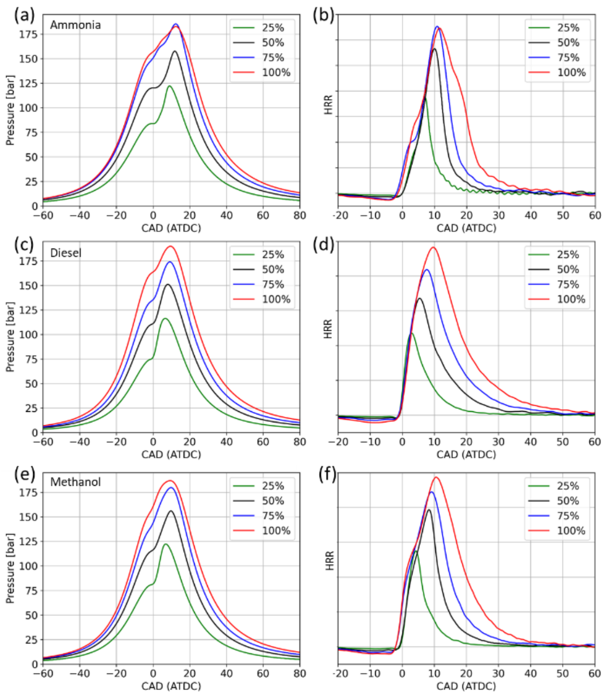

Figure 3. Measured cylinder pressures, from 25% load to 100% load, for the 50 cm bore test engine operating on ammonia are shown in (a). The corresponding pressures of a commercial 50 cm bore engine operating on (c) marine diesel and (e) methanol as fuel. The corresponding heat release rates are plotted in (b), (d) and (f).

The pilot diesel fuel is injected shortly before the ammonia and ignites almost instantaneously, relative to the slow engine speed. From the pressure curves, Fig. 3 (a), a significant pressure increase is observed shortly after 0 crank angle degrees (CAD), indicating that the main ammonia charge is ignited efficiently by the pilot flame. The measured pressure rise due to combustion is below 40 bar, and thus within the desired range for this type of engine. The HRR indicates that ammonia burns at a rate comparable to that of diesel and methanol. The ammonia injection system was designed to provide a fuel delivery rate matching that of a comparable diesel engine. A large-bore marine diesel engine operates mainly in the mixing controlled regime – i.e. the fuel is burnt while it is injected. As load is increased more fuel is delivered by extending the injection duration, resulting in increased combustion duration. The global air/fuel ratio is lean, with lambda decreasing from around 3 at 25% load to around 2 at 100% load. The methanol case, Fig. 3 (e) and (f), follows the same dual-fuel concept as ammonia, with a small diesel pilot used for ignition. The main characteristics of both cylinder pressure curves and HRRs are quite similar, indicating that the NH_3 is ignited and combusted in a similar manner as in a commercial marine engine operating on diesel or methanol. A very positive observation is that the decay of the HRR of NH_3 is as fast as that of methanol, indicating an efficient burn out of the fuel. The short and intense HRR of ammonia indicates that a high thermal efficiency can be achieved also for ammonia.

3.2 Optical visualisation

The dual-fuel diesel combustion mode of ammonia was also verified by the high-speed recording in Fig. 4. Natural flame emission was captured at 20000 frames per second using a high-speed camera. The camera was coupled to a borescope in order to achieve optical access [34]. The ignition and propagation of the diesel pilot is seen in the first four frames. A small unburnt NH_3 cloud, illuminated by the diesel flame, can be seen faintly in the left part of the fourth frame. In the fifth frame the first visible flame emission from the NH_3 flame can be observed, as the ammonia cloud is ignited by the diesel pilot flame. In the following frames the ammonia flame propagates quickly. The ammonia flame appears less luminous than the diesel flame due to its weaker intensity compared to the black-body radiation from the soot in the diesel flame. The diesel injection ends after the tenth frame, after which the last islands of diesel burn out. The ammonia combustion continues and grows dimmer and dimmer as the flame is spread out, cools down and is transported around the cylinder by the swirling in-cylinder flow. After the tenth frame the flame has grown outside the field of view. This image sequence clearly demonstrates that directly injected ammonia is ignited efficiently by a small

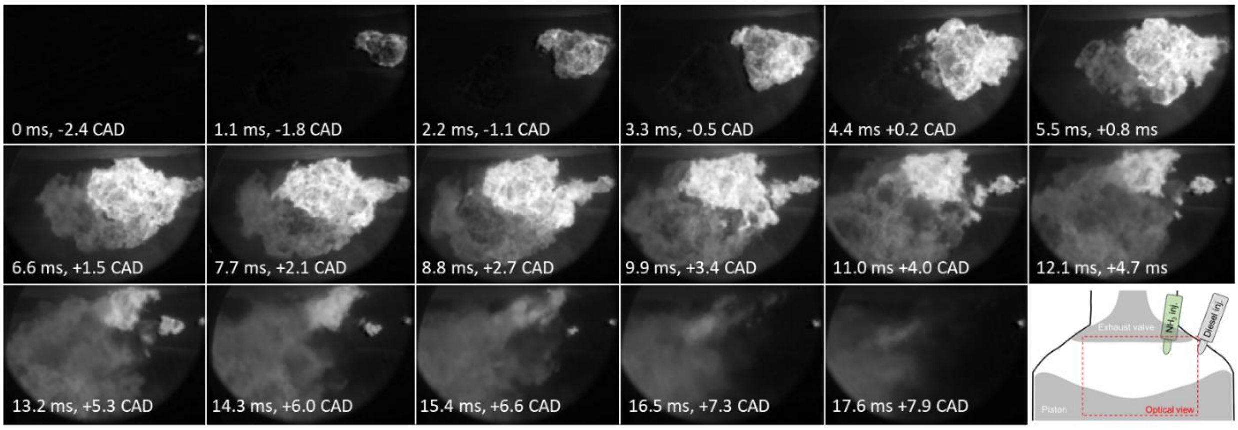

Figure 4. High-speed image sequence of natural flame emission, recorded within a single cycle at 50% engine load. The positions of the ammonia and diesel pilot fuel injectors, within the dashed viewing area, are indicated in the drawing the bottom right. The brighter flame to the right corresponds to diesel pilot combustion, and the dimmer flame to the left to ammonia combustion.

diesel pilot flame, and that a self-sustaining non-premixed NH_3 flame is established after the end of the diesel pilot injection. This is completely analogous to the process in other marine dual-fuel engines of this type, e.g. when operating on natural gas [7,34] or on methanol [9].

3.3 Combustion stability

In order for NH_3 to become a commercially applicable marine fuel, ignition and combustion processes must be stable and robust under varying operating conditions, in order to handle the dynamic performance requirements characteristic of ship propulsion. The stability of the NH_3 combustion process is illustrated in Fig. 5, which shows variations in cylinder pressure at 50% load for operation on (a) ammonia and (b) diesel. The cycle-to cycle stability when operating on ammonia is similar to that of operation on diesel fuel. The dashed lines correspond to one standard deviation up and down from the average cylinder pressure curve and thus indicate the cycle-to-cycle variations in cylinder pressure. The relative standard deviation at maximum cylinder pressure is around 1.26 % for NH_3, compared to 1.09% for diesel under similar operating conditions. The cycle-to-cycle stability of a two-stroke diesel engine is thus preserved, which ensures that well established design limits and control concepts can be followed for a commercial ammonia two-stroke engine. Some of the fine scale oscillations on the pressure traces, right after TDC, are caused by acoustics in the channel leading to the pressure sensor in the test setup.

In order to investigate the sensitivity of NH_3 combustion to compression ratio, the effect of reducing the effective compression ratio is illustrated in Fig. 6. This ratio is changed from 54.5 to 25, corresponding to a reduction in effective compression pressure ratio (P_{comp} / P_{scav}) by more than half. Engine operation at 50% load would normally be in the upper part of this range for this type dual-fuel engine. The NH_3 is efficiently ignited and combusted even at the lowest compression ratios, as indicated by the HRR rate which hardly changes shape – it only retards by a few CAD. This illustrates a good process stability for the NH_3 combustion.

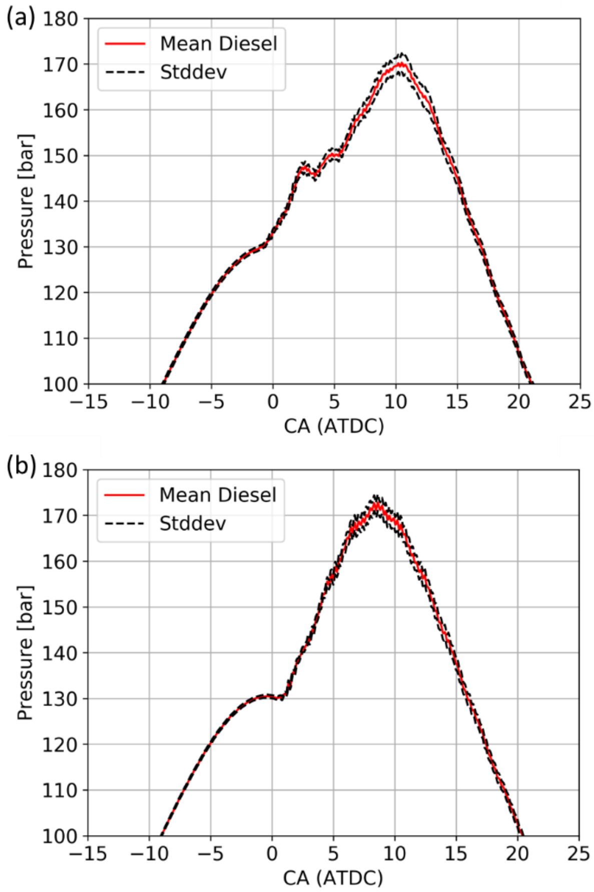

Figure 5. Cycle-to-cycle variations in cylinder pressure at 50% load for operation on (a) ammonia and (b) diesel

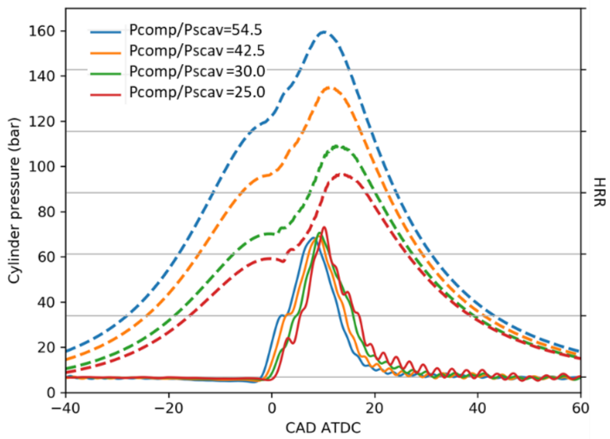

Figure 6. Response to variations in effective compression ratio (P_{comp}/P_{scav}).

The ammonia combustion process was also found to have a diesel-mode like robustness to changes in air excess ratio, pilot timing, scavenging quality, and lubrication mode. The ammonia combustion also successfully copes with the heavy- and light-running needed for accelerating and decelerating a ship. In Fig. 7 the operating regimes covered during tests are outlined. Stable NH_3 combustion was observed under all those conditions. For the propeller curve demonstrated in Fig. 3, the mean indicated pressure (MIP) was 18.5 bar at 100% load. In separate tests, operation up to 23.5 bar MIP was demonstrated. Stable operation on ammonia was observed at loads down to 10%, which is the normal limit of secondary fuel mode operation for a marine dual-fuel engine.

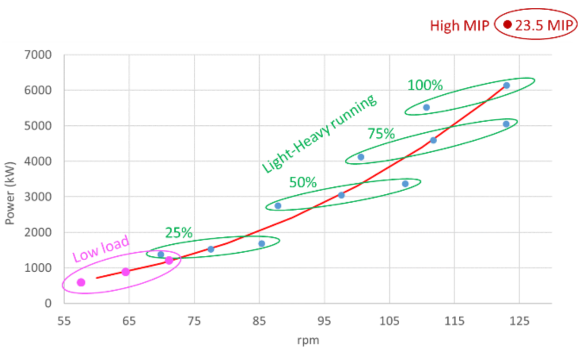

Figure 7. Combustion stability validated over a wide range of conditions.

3.4 Emissions

The three emissions of main interest from an engine operating on ammonia are unburnt ammonia, laughing gas and nitrogen oxides. Unburnt ammonia in the exhaust requires active reduction measures in order to comply with safety standards and also represents a loss of fuel efficiency. N_2O on the other hand is a greenhouse gas which is 265 times more potent than CO_2 [35], and emission levels must be kept very low in order to preserve a GHG benefit. Nitrogen oxides are normally grouped together as NO_x, with NO and NO_2 being the main constituents. For marine engines the NO_x emissions are regulated through the IMO MARPOL convention [36].

3.4.1 Ammonia slip

There can be several different sources of unburnt ammonia in the exhaust gases leaving the cylinder, including incomplete combustion, flame quenching in the bulk gas or in crevices, and leakages from the fuel injector. Ideally as much of the ammonia as possible should be burnt in the cylinder, as any unburnt ammonia in the exhaust lowers the combustion efficiency. In Fig. 8 (a) the NH_3 emissions are plotted as a function of load for four different injector designs, with varying internal flow geometries. Types 1-3 are based on a commercially proven design, whereas type 4 is a new design prototype specifically developed for ammonia. The design evolution from injector 1 to 4 leads to a reduction in NH_3 emissions, especially at low load. At 25% load the NH_3 emissions are 95% lower when using injector 4 compared to injector 1. As the NH_3 is only injected on one of the four cylinders during tests, the emissions are consequently diluted by the exhaust gases from the other three cylinders. For a full engine operating on NH_3, emission levels would be expected to be around four times higher, so that injector 3 would emit around 350 ppm of NH_3 at 100% load (before the SCR unit in a full installation). Compared to previous reports from smaller IC engines[22,24,25,26,32] the lowest NH_3 emissions observed here are 3-60 times lower. The low emissions are likely due to the large combustion chamber's small surface-to-volume ratio and the strong in-cylinder swirl, which helps to keep the flame away from the combustion chamber walls. In this way flame quenching and heat losses are minimised. This in combination with the long residence times in the slow-speed engine, which leaves time for the relatively slow ammonia combustion to complete, likely explains the low emissions of unburnt NH_3 observed. An ammonia engine will always be fitted with a selective catalytic reactor (SCR), which will further reduce the NH_3 slip to acceptable levels.

In Fig. 8 (b) the NH_3 combustion efficiency, calculated from the measured ammonia flow into the cylinder and the ammonia slip in the exhaust, is plotted. The diesel pilot contribution was not included in this estimate. For injector 3 a combustion efficiency above 98% is achieved at 25% load, peaking at around 99.5% at full load. For the prototype injector 4 combustion efficiency is above 99.7% over the entire load range tested.

This combustion efficiency is much higher than that achieved previously in smaller IC engines, where it has typically remained below 90% [22,25].

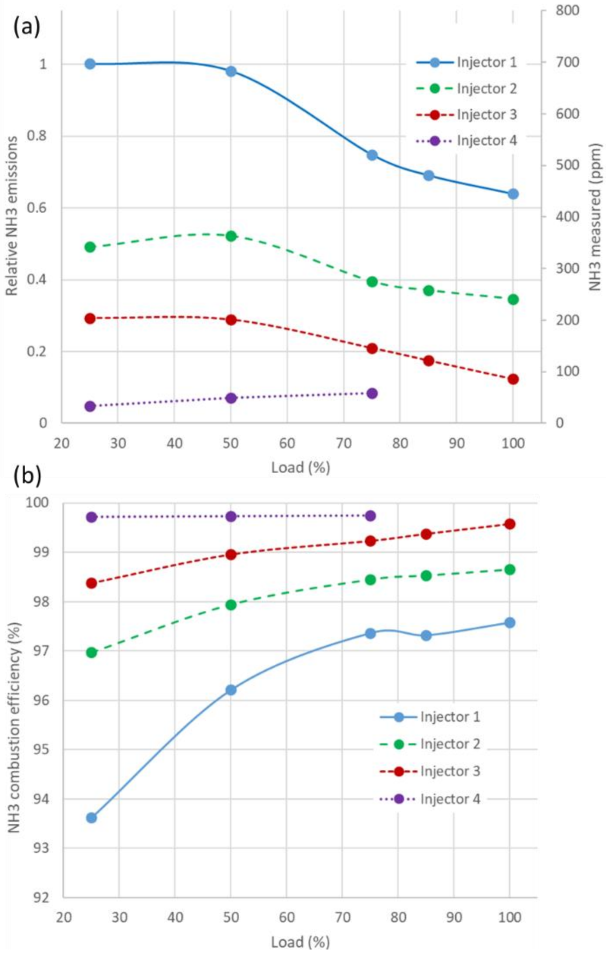

Figure 8. (a) Measured NH_3 emissions for four different fuel injector designs. Exhaust gases from cylinder four are diluted by the other three cylinders operating on diesel. (b) NH_3 combustion efficiency for the same fuel injectors.

3.4.2 NO_x emissions

In Fig. 9 the specific NO_x emissions for operation of the test cylinder on diesel and NH_3 are plotted as a function of engine load. The NO_x emissions from ammonia combustion were found to be 40%-75% lower than for diesel combustion. The reduction is thought to be the combined result of reduced thermal NO_x formation, as ammonia flame temperatures are lower than diesel flame temperatures [26], and locally fuel rich conditions [20]. The cycle averaged NO_x emissions for the diesel operation are around 11.7 g/kWh, well below the Tier II limit of 14.4 g/kWh [37]. Even though the NO_x emissions in NH_3 mode are much lower, the cycle averages exceed the IMO Tier III limit of 3.4 g/kWh by around 15%. An SCR will thus be required for achieving NO_x compliance in emission control areas.

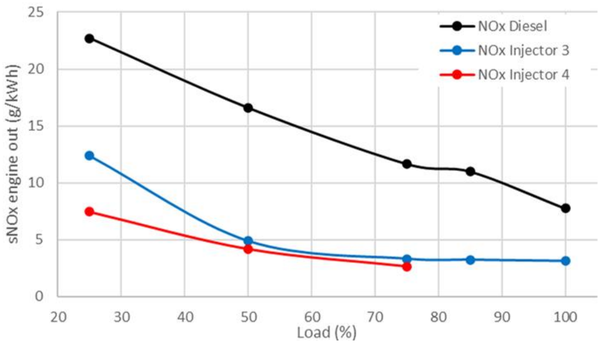

Figure 9. Specific NO_x emissions, of NH_3 test cylinder, over the load curve for operation on both diesel and NH_3.

NH_3 emissions in the exhausts emitted will always be much lower than these reported here, as a SCR will be mounted on the exhaust side. A SCR is commonly used for reducing NO_x emissions, using urea or ammonia as a reducing agent. In both cases NH_3 is the active chemical in the de-NOx reactions. Efficient reduction of both NO_x and NH_3 requires that the two are evenly balanced in molar ratio, assuming that NO makes up most of the NO_x. Since a specific level of NO_x emissions are permitted [37] the goal is to ensure NH_3 levels slightly below the NO_x levels in the raw exhaust gases leaving the cylinder. A small additional amount of NH_3 or urea could then be dosed before the SCR in order to actively control the balance between the two species, thus achieving regulatory emission limits.

3.4.3 Laughing gas

Laughing gas is a critical emission from combustion of NH_3, as it has a large GHG potential. Previous applications of NH_3 to IC engines have typically resulted in significant N_2O emissions [22,24,25,26,32], which limits the GHG reduction potential of those engine concepts. In Fig. 10 (a) the measured N_2O molar concentrations in the exhaust, for injector 3, across the load curve are plotted. The N_2O emissions are highest at 25% load and fairly constant at higher loads. Due to the dilution effects of operating one cylinder out of four on ammonia the ppm values from a full engine would be around 4 times higher. At high load this would correspond to around 3 ppm of N_2O. This is around 10-30 times lower than previous reports [22,24,25,26,32]. Emissions from injector 4 are at a similar level. The corresponding GHG impact from the measured N_2O emissions is indicated on the left hand axis in Fig. 10 (a). It represents 1.5%-2.5% of the GHG contribution from CO_2 emissions when operating on diesel under the same operating conditions. Laughing gas emissions are believed to be low in this dual-fuel process, as a high stratification minimises the regions with temperature and chemical composition promoting

N_2O formation which are typically encountered during pre-mixed operation [37].

In Fig. 10 (b) the measured N_2O and NH_3 emissions at 50% load are plotted for a wide range of operating conditions, injection timings, and injector designs. It is clear that the N_2O is uncorrelated to NH_3 emission levels. The data show that it is possible to achieve low N_2O emissions (around 2% GHG equivalence) under a large number of operational conditions and injector configurations. The highest N_2O values shown (corresponding to approximately four times 6 ppm for a full engine, or 14% GHG equivalent) were observed when injecting the diesel pilot after the start of the NH_3 injection, which leads to locally pre-mixed ammonia before ignition. Under normal operation an ammonia engine would not suffer from such high N_2O emissions, as there is no benefit in operating the engine with such injection timings.

3.5 Greenhouse gas reduction

There are several contributing factors to the total GHG footprint of operating an ammonia engine. The first, which is not considered here, includes any GHG emissions associated with the NH_3 production, transportation and logistics. The use of renewable energy is essential for minimising impacts at this stage [10,11,12,16,17]. Furthermore, there are direct GHG contributions from N_2O and CO_2 in the exhaust gases. In Fig. 11 the estimated GHG equivalencies, for both these contributions, are plotted for two different diesel pilot amounts. The reduced amount of diesel pilot directly improves the GHG reduction, through decreased CO_2 emissions. In principle this contribution could be removed completely, by using a renewable hydrocarbon fuel for the pilot flame, such as a bio-fuel or an electro-fuel. The N_2O emissions will ultimately determine the limit of the highest GHG savings possible, even when using completely CO_2 neutral pilot fuel. The GHG contribution from the potent greenhouse gas N_2O is plotted in blue, and is less than 2% in this case. The total GHG reduction observed for smaller pilot amounts is above 95%, which is a substantial improvement compared to previous reports, where GHG reductions of 35%-80% were achieved [22,24,25]. For a commercial dual-fuel engine the pilot amount is typically around 5%, which would lead to GHG reductions well above 90%.

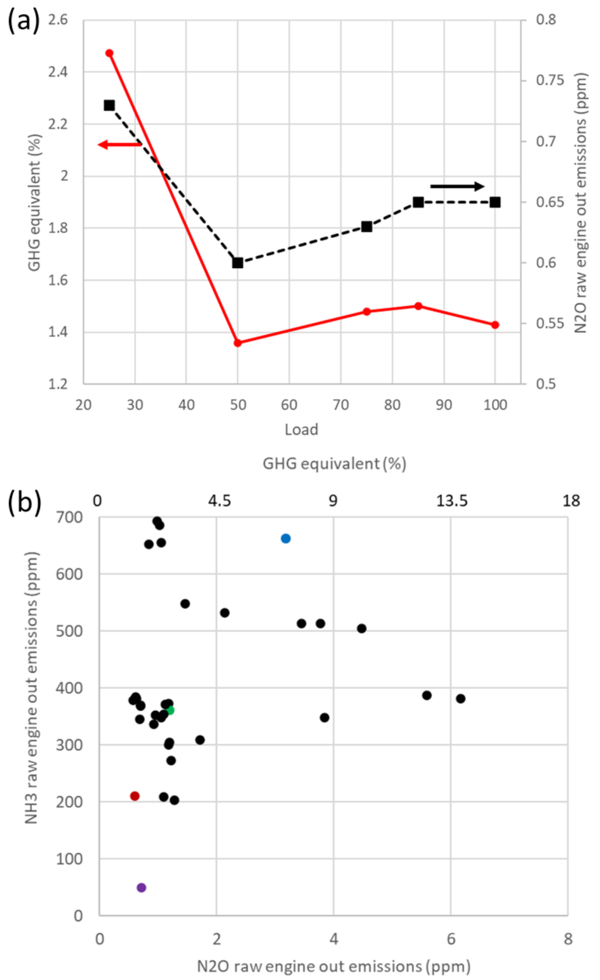

Figure 10. (a) N_2O molar concentrations across the load curve for injector 3. Left y-axis: GHG equivalent emissions compared to operation on diesel. Right y-axis: measured N_2O emissions from test cylinder, diluted by the other three cylinders. (b) Scatter plot of N_2O versus NH_3 emissions for all tests conducted at 50% load, the coloured dots correspond to the tests at 50% load shown in Fig. 8 (a).

Figure 11. GHG equivalent emissions at 100% load for injector 3, using two different pilot amounts. Emissions are compared to normal diesel operation. Blue: contribution from N_2O. Red: contribution from pilot CO_2.

3.6 Efficiency

Energy efficiency is equally important as the direct GHG emissions since the chemical energy bound in the green fuel must be converted to mechanical work in an efficient manner in order to reduce the GHG footprint of the entire ammonia fueled propulsion system. The thermal efficiency of a modern two-stroke marine engine is typically around 50% [6]. The intense heat release rate, illustrated in Fig. 3 (b), in combination with the high NH_3 combustion efficiency, illustrated in Fig. 8 (b), indicates that ammonia can be an efficient fuel for a dual-fuel combustion process. A comparison of indicated thermal efficiencies for operation on diesel and NH_3 as fuels, see Fig. 12, reveals similar efficiencies. This indicates that the energy efficiency of an ammonia burning two-stroke marine engine will be comparable to that of the corresponding diesel engine, and will be well above that of smaller IC ammonia engine designs demonstrated in the past. The absolute values of indicated thermal efficiencies plotted in Fig. 12 are all a bit lower than those of modern commercial two-stroke engines, due to the older mechanical design of the test engine.

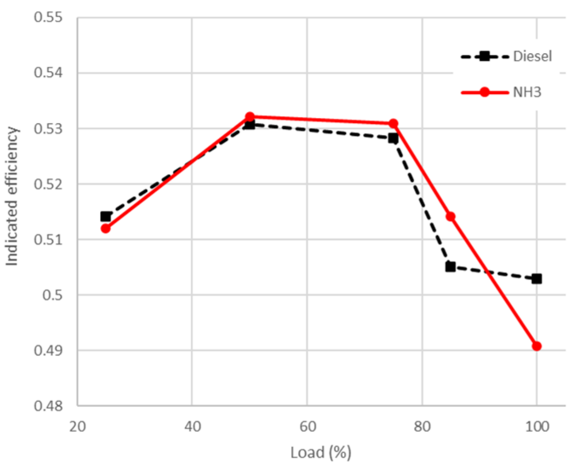

Figure 12. Indicated efficiencies for operation on diesel fuel and on NH_3, using injector 3.

The indicated thermal efficiency was calculated from the mean effective pressure, P_e, the displacement volume V_d, the amount of fuel injected in a single cycle, m_{fuel}, and the lower calorific value of the fuel LCV:

$$\eta_{th} = \frac{P_e \cdot V_d}{m_{fuel} \cdot LCV} \quad (1)$$

3.7 Cylinder conditions

Good cylinder conditions are a result of many factors, ranging from the design on the combustion chamber parts, engine process, lubrication system and the associated lubricants, as well as the fuel. During the duration of the LGI-A tests, two kinds of cylinder oils were tested and the cylinder condition was monitored by regular scavenge port inspections, as well as drain oil sampling and analysis. There were no ammonia related issues experienced with lubrication, sampling of drain oil or with the samples. No smell of ammonia was detected during the scavenge port inspections. Inspections also revealed that there were no significant differences in cylinder condition between the test unit operating on NH_3 for approximately 200 running hours compared to reference units operating on diesel. The test unit's three cermet-coated piston rings, ring-lands, top-land and piston appeared to be in acceptable condition, see Fig. 13. The analysis of the drain oil samples showed that iron and BN levels were as normally expected from test-engine running conditions.

Figure 13. Photos from cylinder inspection of the NH_3 test cylinder.

4 FULL ENGINE TESTS

Final verification of the LGIA engine concept and further optimisation will be carried out on two full test engines. The first one is the 4T50ME-X, which has been rebuilt to ammonia operation on all cylinders, see Fig. 14.

Figure 14. Photo of MAN B&W 4T50ME-X rebuilt to full engine operation on ammonia.

The installation also includes a SCR unit, in order to reduce NO_x and NH_3 emission levels, see Fig. 15. The full engine test platform will allow validation of emission and performance values, optimisation of the NH_3 combustion concept, and maturing of the control system with respect to joint engine and SCR control.

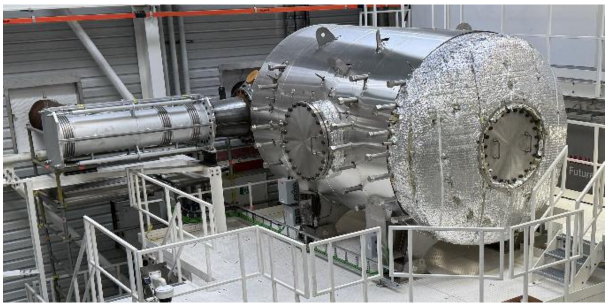

Figure 15. SCR for 4T50ME-X full engine testing.

The cylinder pressures for the first full NH_3 engine operation, with the SCR, are plotted in Fig. 16. Laughing gas and NOx emissions were confirmed to be low for full engine operation. An energy efficiency similar to diesel operation was also confirmed.

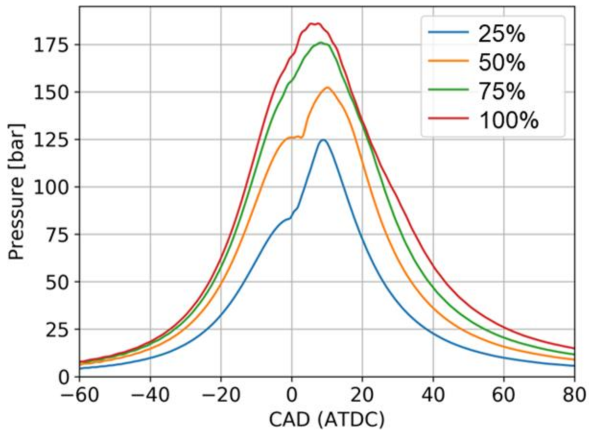

Figure 16. Measured cylinder pressures, from 25% load to 100% load, for full engine NH_3 running on the 4T50ME-X with SCR.

The second engine to be used for full-scale R&D tests is the 7S60ME-C10.5-LGIA, built by Mitsui E&S Co., Ltd. (see Fig. 17).

Figure 17. Photo of MAN B&W 7S60ME-C10.5-LGIA.

5 FUTURE OUTLOOK

5.1.1 Market introduction strategy

A number of pilot projects with G50, S60, G60, G70 and G80 based NH_3 engines are on-going in Korea, Japan and China. MAN Energy Solutions wants to obtain positive seagoing experience from a number of MAN B&W ammonia engines before they are fully released in the engine catalogue. The service experience will be used to introduce potential design updates and improvements for both main and auxiliary systems, in order to safeguard the best use of ammonia as a marine fuel. The actual time schedule will be determined by shipyard delivery schedule. Currently the sales release is expected to take place at the end of 2026.

MAN Energy Solutions is working on offering retrofit conversion of ME-C engines to use ammonia as fuel. The first retrofit package will be ready once the commercial design is ready for full sales release. Ammonia-ready vessel designs will ease the process and complexity of such future retrofit projects.

5.1.2 Regulation of exhaust emissions for ammonia engines

5.1.2.1 NH_3 – IMO has not yet introduced emission limits for NH_3. There is, however, increased focus on the topic and the introduction of emission limits for NH_3 is expected to be on IMO's official agenda within the coming years. The IMO SCR Guidelines requires the slip of reductant (NH_3) to be minimized but does not set any limit values for the reductant slip.

5.1.1.2 N_2O – New EU regulation on GHG emissions from shipping [38,39] targets N_2O and CH_4 in addition to CO_2. IMO is expected to introduce new GHG regulation in 2027, which will also target emissions of N_2O, CH_4 and CO_2. The contribution of CH_4 and N_2O to the total GHG emissions is calculated based on their 100 years global warming potential (GWP 100).

6 CONCLUSIONS

Extensive testing of NH_3 as a fuel in a full-sized marine two-stroke engine revealed that the ammonia could be ignited effectively and in a stable manner using a small diesel pilot flame over the entire load range of the engine. A self-sustained combustion of the NH_3 jets, in a diesel like fashion, was observed. The cycle-to-cycle stability of the combustion was comparable to that for normal diesel, and the combustion process demonstrated a high robustness to variations in the ignition process as well as to variations in the compression ratio. The heat release rate analysis revealed that the combustion intensity, duration and burn-out was similar to that in commercial two-stroke dual-fuel engines operating for example on methanol. The promising results obtained, achieved on a proven engine design which is used for propulsion on a majority of all deep sea ships, demonstrates that the shipping market could transition with confidence into CO_2 free operation in the near future – as long as green ammonia produced from renewable energy sources becomes available on a large scale.

In contrast to previous work on smaller sized engines, many of which use the Otto principle rather than the Diesel principle, an efficient combustion with NH_3 energy fractions exceeding 90%, combustion efficiencies as high as 99.7%, and with N_2O emissions as low as a few parts per million was obtained in this work. The low laughing gas emissions are crucial in order to achieve a large GHG benefit, with a GHG reduction potential exceeding 90% at full load demonstrated here. There could be several reasons behind the efficient burn-out of ammonia and the low N_2O emissions. The slow revolution speed, 77-123 rpm, leaves sufficient time for ammonia combustion to be completed despite ammonia's poor flammability and low flame-speed. The large engine size, 50 cm bore diameter, results in a favourable surface to volume ratio of the combustion chamber. This in combination with a strongly swirling in-cylinder flow helps to keep the directly injected ammonia, as well as the ammonia flame, away from the walls, which could otherwise lead to quenching and incomplete combustion. The low N_2O emissions are an effect of limiting the regions having a temperature and chemical composition promoting N_2O formation [38] in the highly stratified dual-fuel diesel-cycle process.

Several additional improvements to the present engine design could be made, in order to reduce emissions further. The injection system is currently being refined further, to allow decreased emissions of unburnt NH_3 in the commercial applications. This would represent both a fuel saving and also allow more margin for SCR control from the reduced NH_3/NO_x ratio. In this first demonstration of ammonia operation, fossil diesel fuel has been used for the pilot flame. In order to further reduce the GHG footprint, the pilot fuel could easily be replaced by a renewable hydrocarbon fuel, such as bio-fuel or synthetic power-to-x diesel fuel.

Full scale testing is currently progressing on the 4T50ME-X and the 7S60ME-C10.5-LGIA engines and a number of pilot projects on 50-80 cm bore engines are underway. The first service experience is expected in the first half of 2026, followed by a full sales release at the end of 2026.

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