Emission Control
MAN B&W Two-stroke Diesel Engines

Contents:

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Abstract

The worldwide focus on fuels is generally increasing because of the focus on exhaust gas emissions.

During more than 10-15 years, the authorities have been focused on establishing rules for the exhaust gas emissions from marine engines, and today it seems that IMO Annex VI will be ratified in the course of 2004/2005. Hence, the marine industry will be under international regulation.

Compliance with IMO Annex VI requires the engines to be within the given NO_x level limits documented in a technical file following the engine in operation.

In order to give operators a unified technical file to be followed by MAN B&W licensees, a procedure has been developed by MAN B&W and accepted by the flag states' representatives, the Classification Societies. The unified technical file is described in a separate chapter.

Until now, local rules have been introduced for areas such as Sweden, Norway, and the harbour of Hamburg, where for example a harbour-fee reduction is used as an incentive for the use of low-sulphur fuel, but with limited impact on the environment, especially with regard to emissions from ships in international operation.

A general worldwide emissions limitation seems to be the only way that all countries can benefit from a reduction in emissions. Emission limits must follow state-of-the-art technology and the ability of the market to adapt to such limits.

It is correct that emission limits can force the technology to be developed, but then the solution chosen will not necessarily be the optimum one. And the system chosen on ships built will, on average, stay there for the ship's lifetime, which can be more than 25 years.

Methods to reduce exhaust gas emissions, and techniques such as selective catalytic reduction and water emulsification are already in use on MAN B&W two-stroke engines.

The authorities have so far focused on NO_x and SO_x, but as soon as IMO Annex VI has been ratified, more attention will be given to components from the exhaust, such as HC, particulates, CO and CO_2.

These considerations involve not only the fuel used and the engine design, but also operational issues and the use of cylinder lube oil are influencing factors.

With regard to lube oil, MAN B&W has introduced the so-called Alpha Lubricator, which enables the operator to make a considerable reduction in the cyl. lube oil consumption and, thereby, achieve a reduction in particulate emissions.

Operational-wise, MAN B&W Diesel has proved that when installing a two-stroke engine using HFO and a reliquefaction plant on LNG/LPG carriers, CO_2 and SO_x will be reduced and, at the same time, there will be a remarkable reduction in operational costs, as the boil-off gas will be regained as gas and put back into the tanks.

Another operational influencing factor is the one where reduced speed of vessels close to shore could reduce emissions by approx. 20% per 10% reduction of speed.

The latest and most far-reaching change that has been made over the years in our engine programme is the introduction of the electronically controlled engine.

With an electronically controlled engine, the fuel injection and exhaust gas valve activation is fully programmable, so that the optimum reduction of exhaust emission levels can be met at all engine loads.

With turbo generator and turbo-compound system plants, the prime mover concept can reduce the plant's consumption of fuel and, beneficially, achieve a reduction of emissions. The concept utilises the high-efficiency air flow from the turbochargers for a power take-off or power take-in system.

The next generation of emission control systems, which is on the drawing board and on the test facility, involves systems integrated into the engines, where NO_x is reduced by operating with water in the engine intake air, also called the HAM "Humid Air Motor" principle, and the use of EGR (exhaust gas recirculation).

These methods, so far, look very promising, and a reduction of NO_x of up to 50% and a reduction of particulates and HC seems achievable, even though final tests and production maturing still need to be taken care of.

The reduction of the sulphur content in HFO is so far the most efficient method to reduce SO_x, and this reduction has therefore been the reason for a lot of considerations from the Industry. The oil companies may need to change their equipment to low-sulphur fuel production, and the shipowners could face considerably higher fuel costs.

The technique for removing SO_x from engine exhaust gas on ships has proved to be very expensive and complicated and does not seem to be a viable solution with the systems being used today.

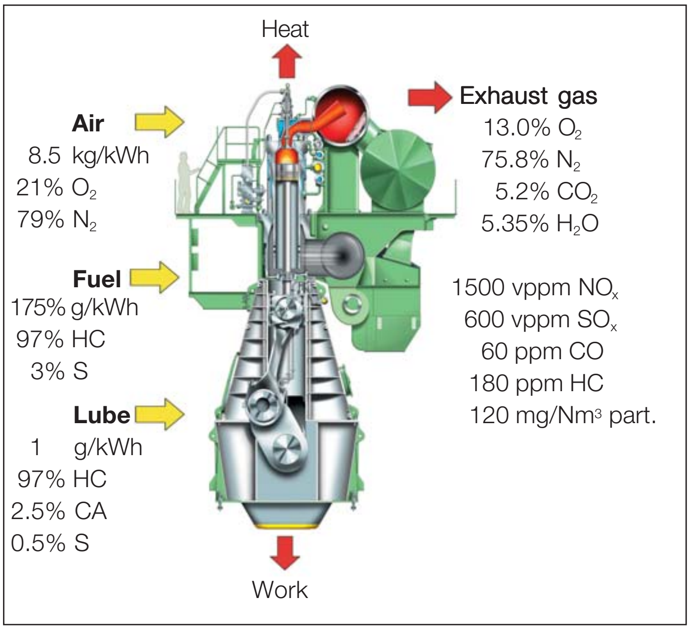

Fig. 1: Flow process and typical exhaust gas composition

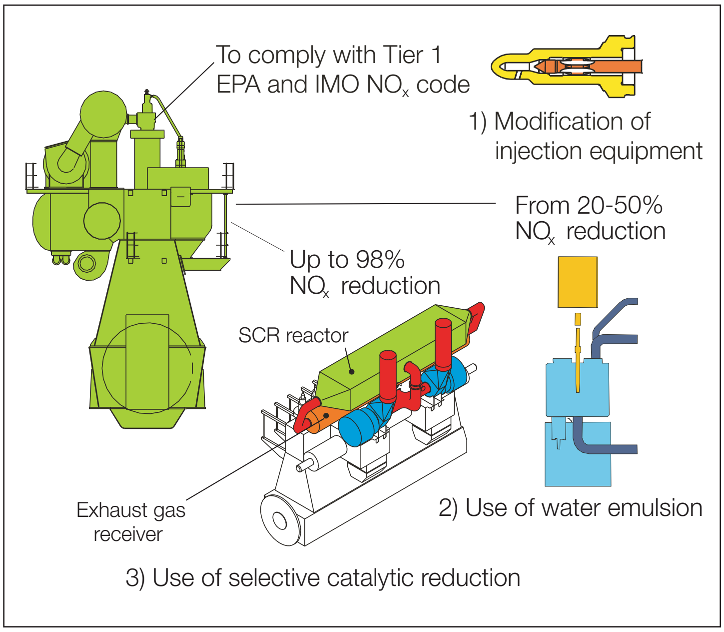

Fig. 2: NO_x reduction methods

Another consideration for ships in service is the operation on different fuels with different sulphur levels. Ships were previously designed for HFO operation only, with relatively small tanks for distillates. If two fuel grades are to be used, there will be a change-over situation when operators change from one emission zone to another, e.g. 4.5% sulphur to 1.5% sulphur, which is the limit in the low-sulphur restricted areas.

MAN B&W Diesel participates in a project in the European Union concerning the use of low-sulphur fuels and the impact of doing so on the marine industry.

Emissions

When talking about exhaust gas emissions from ships, the relevant components are NO_x, SO_x, CO, CO_2, HC, and particulates, see Fig. 1.

So far, particulates and HC, together with NO_2 and water vapour (constituting visible smoke) are being judged by not so accurate opacity measurements. At this stage, and probably for many years ahead, NO_x and SO_x will be the only components that will be given international measurable limits in the marine market. It is expected that HC and particulates will follow, but it is uncertain when this will happen.

The industry is still considering the optimum methods of controlling HC and particulates, and the method of measuring also remains to be agreed upon. The situation is different for power plants, for which there are often limits to all polluting components of the diesel exhaust gas.

It should be noted that pollutants are usually measured as concentrations, whereas rules are formulated as absolute emission factors (mass per unit, time or power) arrived at by calculation, based on the concentration measurements.

Over the years, MAN B&W has worked with the exhaust gas emission issue in order to develop means to reduce the levels so as to comply with limitations which can be expected to come.

There are, in principle, two ways to lower (NO_x) emissions, viz. primary and secondary methods.

While primary methods prevent the NO_x and other pollutants from being formed, secondary methods aim at reducing or removing the already formed pollutants.

The most relevant proven methods for NO_x reduction are: fuel valve and nozzle optimisation, timing tuning, fuel water emulsification, Exhaust Gas Recirculation (EGR), and Selective Catalytic Reduction (SCR), see Fig. 2.

Primary Methods

Fuel valve and nozzle optimisation and timing control

When the engines are delivered from the engine builder, they have, unless otherwise specified, been prepared to meet the IMO speed-related NO_x limit curve. This is achieved with NO_x-emission-optimised fuel injection valves and nozzles and, if necessary, a slight delay in fuel injection. For the fuel valves, the number and size of the spray holes are the influencing factors, whereas for HC and particulate control, the influencing factors are the valve design and, in particular, the sac volume (explained later).

Compliance with the IMO rules implies no or a slight increase in SFOC for some engines. Therefore, the fuel consumption tolerance has been changed for IMO compliant engines from 3 to 5%.

Technological advances developed over the last decade have made it possible to commercially launch what used to be referred to as the electronic engine. In MAN B&W Diesel's engine portfolio, this concept is named ME/ME-C, comprising a range of low speed engines with the same bore, stroke and process parameters as their MC/MC-C counterparts. The "E" range comprises engines with on-line continuous control of the timing of the fuel injection and exhaust valve opening and closing, by means of electronic control acting via a high pressure hydraulic oil interface. Therefore, such engines have no conventional camshaft. The ME-C engine is shown in Fig. 3.

The operational advantages are outlined in Fig. 4, and particularly important, with a view to emissions, is that the on-line timing control allows better NO_x control over a wider load range, and lower part load SFOC and soot emissions.

The next step in emission control from IMO is expected to include a 30% further reduction from present IMO Annex VI limits. The ME/ME-C engine already meets this target, which is within the electronic control range, see Fig. 5. This also means more stable running, particularly at low load.

The benefits are obtained mostly in the control of the fuel injection, where the system, with individually controlled fuel pumps with hydraulic oil activation, allows optimum fuel injection ("free") rate shaping at any load. Hence the fuel injection pressure and, thus, injection intensity is a controllable parameter, contrary to the situation on mechanically controlled engines.

The independently controlled exhaust valve timing adds to the benefit by ensuring a more optimum air supply to the cylinders at any load condition.

The ME/ME-C engines are now gaining monumentum in the market, and practically all types are represented on the reference list, and the first seagoing engine featuring this principle has, with impeccable results, logged more than 8,000 hrs. on board the Norwegian chemical carrier *M/V Bow Cecil* owned by Odfjell.

Fig. 3: S70ME-C engine control system

- Well-proven traditional fuel injection pattern and technology with increased injection rate during the injection period.
- Variable electronically controlled timing of fuel injection and exhaust valves for lower SFOC and better performance parameters.
- Control system offers more precise timing and thereby better engine balance and less noise with equalized thermal load in and between cylinders, minimising the risk of premature need for overhaul.
- Lower rpm possible for manoeuvring.
- Better astern and crash-stop performance.
- Improved emission characteristics, i.e. lower NO_x and smoke values at any load.
- System comprising performance monitoring for longer time between overhauls.

Fig. 4: Advantages of ME-engines

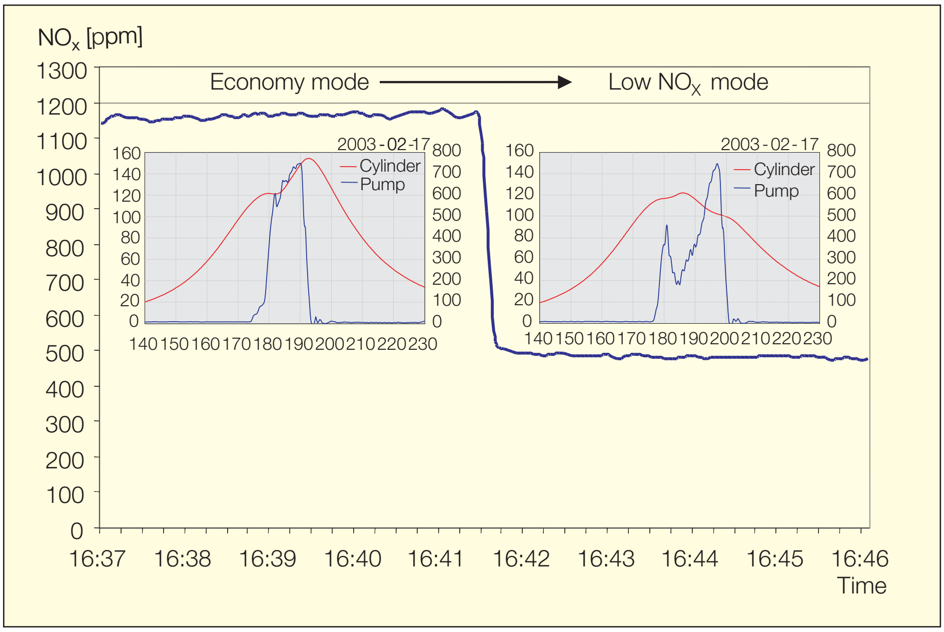

Fig. 5: Mode-change demonstration on a 7S50ME-C engine at 75% load

Smoke evaluation

A traditional measure of the combustion quality, and a traditional way of qualifying the 'emission', is to look at, or to measure, the smoke intensity. The exhaust gas plume, when it leaves the top of the stack, may be visible for various reasons, e.g. due to its content of particulate matter and nitrogen dioxide, NO_2 (a yellow/brown gas), or of condensing water vapour. Although it may be argued that these components are either subject to separate legislation (NO_x, particulate matter) or not harmful (water), it is a fact that smoke and/or opacity limits are traditionally applied in certain countries, e.g. in the USA.

Unfortunately, methods of measuring smoke and opacity vary, and the figures resulting from the different methods are not really comparable.

When considering visible emissions, we should bear in mind that the larger the engine, the more likely it is that the exhaust gas plume will be visible. This is because, for a given Bosch Smoke Number (BSN value), the greater the diameter of the plume, the greater the amount of light it will absorb. For instance, a BSN of 1 will mean almost invisible exhaust gas from a truck engine, but visible exhaust gas from a large, low-speed engine.

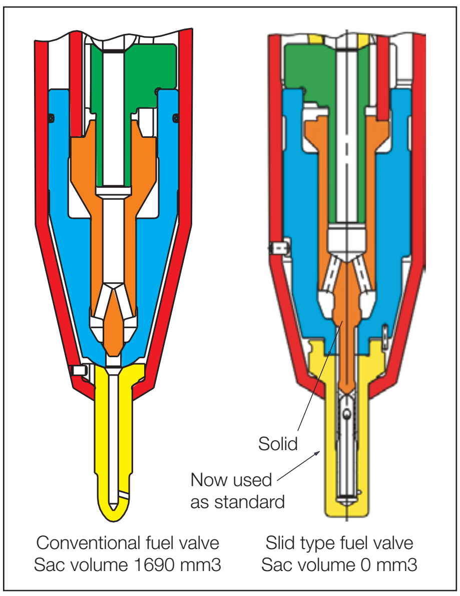

Fig. 6: Fuel valves for K98MC

At transient load and at low load, smoke is often visible, but typical smoke values for the most recent generation of MAN B&W engines are so low that the exhaust plume will be invisible, unless water vapour condenses in the plume, producing a grey or white colour. However, the NO_2 may give the plume a yellowish appearance. As mentioned, low and transient load smoke will practically disappear on electronically controlled engines.

Particulate emissions

Particulate emissions in the exhaust gas may originate from a number of sources:

- agglomeration of very small particles of partly burned fuel,
- partly burned lube oil,
- ash content of fuel oil and cylinder lube oil,
- sulphates and water.

The contribution from the lube oil consists mainly of calcium compounds, viz. sulphates and carbonates, as calcium is the main carrier of alkalinity in lube oil to neutralise sulphuric acid. Once fuel is atomised in the combustion chamber, the combustion process in a diesel engine involves small droplets of fuel which evaporate, ignite, and are subsequently burned. During this process, a minute part of the oil will be left as a "nucleus" comprising mainly carbon. Consequently, particulate emission will vary substantially with fuel oil composition and with lube oil type and dosage. It is therefore difficult to state general emission rates for particulates.

In general, the particles are small, and it can be expected that over 90% will be less than 1 µm when heavy fuel oil is used, excluding flakes of deposits, peeling-off from the combustion chamber or exhaust system walls, which in general are much larger.

Apart from the fact that a smoking engine is not a very pleasant sight, the soot from an engine can cause difficulties, especially if it is "wet" with oil. In such cases, it may deposit in the exhaust gas boiler, especially on cold surfaces, thus increasing the back pressure and representing a boiler fire hazard. Combustion process control, together with appropriate temperature control in the boiler, and frequent cleaning, are the ways to avoid this problem [4].

Hydrocarbons (and trace organics)

During the combustion process, a very small part of the hydrocarbons will leave the process unburned, and others will be formed. These are referred to as unburned hydrocarbons, and they are normally stated in terms of equivalent CH_4 content.

The content of hydrocarbons in the exhaust gas from large diesel engines depends on the type of fuel, and the engine adjustment and design. Reduced sac volume in the fuel valves has greatly reduced HC emissions. The sac volume is the void space in the fuel valve downstream of the closing face, as seen in Fig. 6.

As can be seen from the measurements, the slide-type fuel valve design has quite an impact on HC and particulates.

For compliance with the IMO rules, low-NO_x nozzles are used. For HC and particulate control in general, slide-type fuel valves are used. The latest valves feature both the zero-sac volume and the low-NO_x spray pattern, see Fig. 6.

It should be mentioned that the IMO NO_x-regulation, when ratified, does not apply for ships where the keel was laid before January 2000.

Sulphur content in fuel and particulates in exhaust gas

The sulphur content in fuel oil has a large impact on the particle level in the exhaust gas. IMO has proposed restrictions of sulphur to 1.5% in special areas like the North Sea and the Baltic Sea in northern Europe, and local marine emission rules, e.g. in Sweden and Norway, are aimed at reducing the particulate emission substantially (see also the chapter regarding local marine rules). Tests and analysis of exhaust gas have shown that a high-sulphur HFO can give several times higher particle levels than if the engine is operated on gas oil. A large part of the difference between HFO and DO is related to the sulphur, which together with water forms particulates. This is seen in Fig. 8.

Correspondingly, long time use of lower-than-average sulphur fuels will, contrary to normal marine applications, call for the use of lower BN lube oils in order not to overdose the combustion chamber with deposit-generating additivated oils. This will be particularly relevant for engines operated continuously at high load having less need for SO_x neutralising on the liner surface due to high temperature.

It has been established that a certain level of controlled corrosion enhances lubrication, in that the corrosion generates small "pockets" in the cylinder liner running face from which hydrodynamic lubrication from the oil in the pocket is created. The alternative, no corrosion, could lead to bore-polish and, subsequently, hamper the creation of the necessary oil film on the liner surface, eventually resulting in accelerated wear.

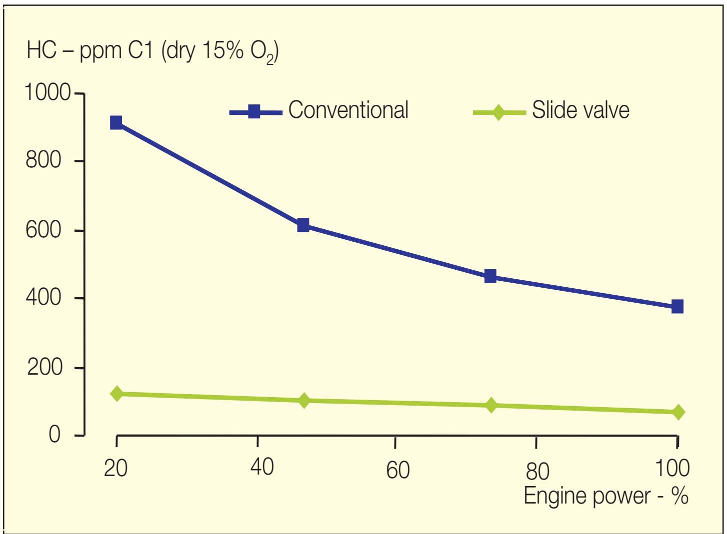

Fig. 7: Hydrocarbon emission, fuel valve comparison – 7S50MC-C

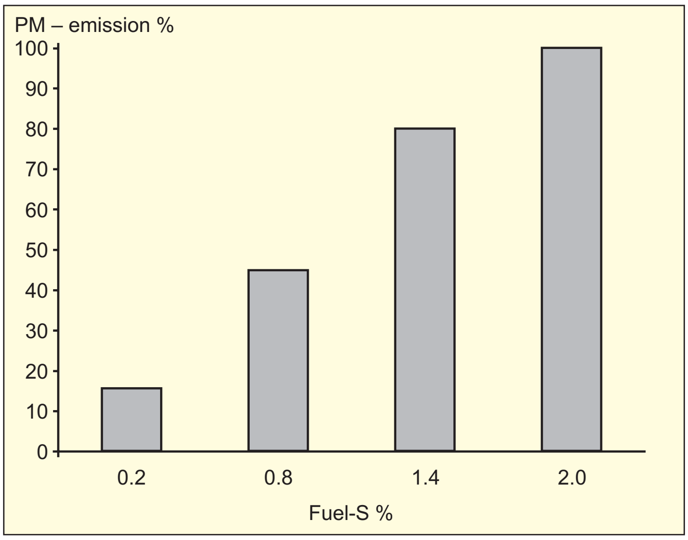

Fig. 8: Emission of particulates as a function of fuel sulphur content

This phenomenon also occurs on trunk piston engines where a bore-polished cylinder liner surface hampers the functioning of oil scraper rings and leads to accelerated lube oil consumption due to the open access to the crankcase oil. Corrosion control – not avoiding corrosion – is therefore crucial, and adjusting the BN to the fuel oil sulphur content is essential particularly on high-load stationary engines.

It should be considered that, irrespective of the sulphur content being high or low, the fuels used in low speed engines are usually low quality heavy fuels. Therefore, the cylinder oils must have full capacity in respect of detergency and dispersancy, irrespective of the BN specified. This is a newly developed technology now mastered by the well-reputed lube oil suppliers, who can individually tailor a cylinder lube oil to the relevant fuel.

Alpha Lubricator

In consequence of the above, the cylinder oil feed rate has an impact on the particulate emission. Tests show that when reducing the cylinder oil feed rate, the particulate emission is also reduced, see Fig. 10.

Cylinder lube oil consumption represents a large expenditure for engine operation, and the reduction of cylinder lubrication is an important development theme. The aim is to reduce the cylinder lube oil dosage, while at the same time maintaining a satisfactory piston ring/liner wear rate and maintaining, or improving, the time between overhauls.

MAN B&W Diesel has achieved this by developing the Alpha Lubricator system, Fig. 9, which is a high-pressure electronically controlled lubricator that injects the cylinder lube oil into the cylinder at the exact position and time where the effect is optimal, which is not always possible with the conventional lubricators of today. Both for marine engines and engines for power generation purposes, very low feed rates have been demonstrated, with oil consumption down to 0.5 g/bhph.

By applying low oil dosage as for the above, emission is lowered, and also less cylinder oil is wasted in the engine, where it could end up in the system oil, resulting in increased TBN and viscosity.

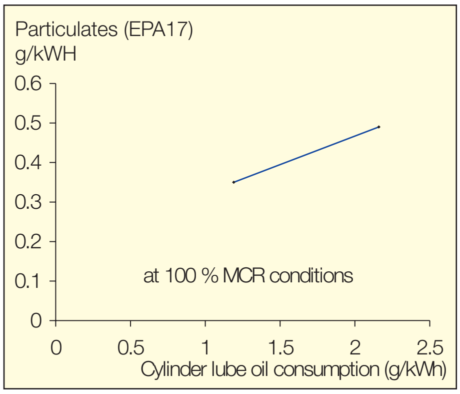

Fig. 10: Particulate emission as a function of cyl. lube oil consumption

Fig. 9: 12K98MC-C with Alpha Lubricator System

CO_2 emission

Emission control has turned into the most important driving force for development.

Hence, this is an area to which extensive development effort is allocated. This emphasises both on NO_x control, SO_x limitation, particulate control and, to an increasing extent, on CO_2 emission, the latter reflecting thermal efficiency.

The so-called greenhouse effect is widely discussed, and the CO_2 concentration in the atmosphere is looked at with some anxiety. In any case, the low speed diesel is the heat engine available for ship propulsion with the lowest CO_2 emission. This is possible simply by virtue of its high thermal efficiency.

One (only) field of application where the industry has not yet taken advantage of the heat-efficient low speed diesel is for the propulsion of LNG carriers. The boil-off rate of modern LNG containment systems is so low that this gas, when burned in the boiler only constitutes about 30-50% of the energy consumed to produce the steam for the turbines. The rest is supplied as heavy fuel.

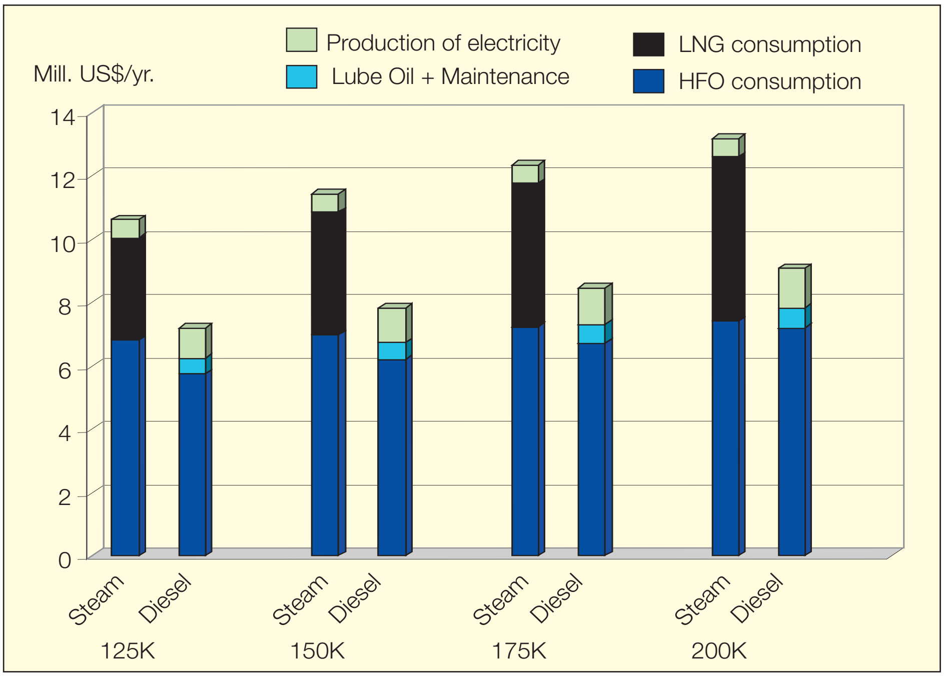

Fig. 11: Operating costs for LNG carriers

By reliquefying the boil-off gas and returning it to the tanks, and by using regular heavy fuel burning low speed diesels for LNG carrier propulsion, the CO_2 emission could be reduced by up to 30%, and the returned gas could be sold for up to USD 3.5 million per vessel per year, as seen in Fig. 11.

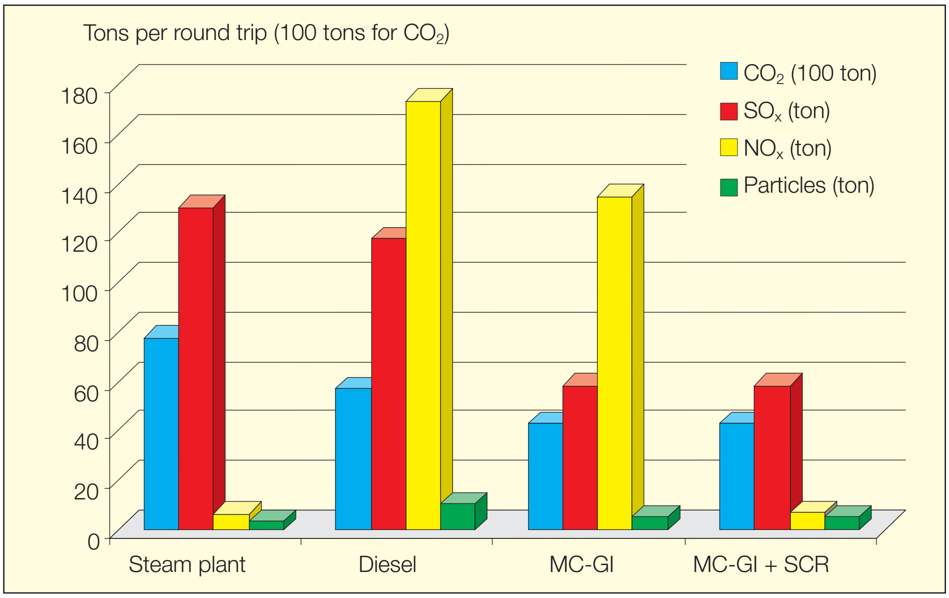

Fig. 12: Round trip emissions, 135,000 m³ LNG carrier

To avoid immobilisation for overhaul of the diesel, a twin engine fully redundant propulsion system as shown in Fig. 13 is proposed. Environmental impact and economic savings are driving this industry towards it.

The turbo-compound system of the two proposed engine alternatives improves the plant efficiency by utilising excess air from the turbocharger to generate electricity to the ship grid, or returning it to the engine shaft as mechanical energy.

For LNG carriers, an alternative to HFO burning engines is dual fuel ME-GI engines, where GI stands for 'gas injection'. If the gas price is considered to be less valuable than the HFO/DO used on the HFO burning engine, a ME-GI can be installed instead to burn the boil-off gas (BOG).

The ratio between HFO and BOG used is variable over 30% load, and can, as such, be adjusted to the actual BOG amount available. This is described much more in detail in a MAN B&W Diesel paper, ref. [5].

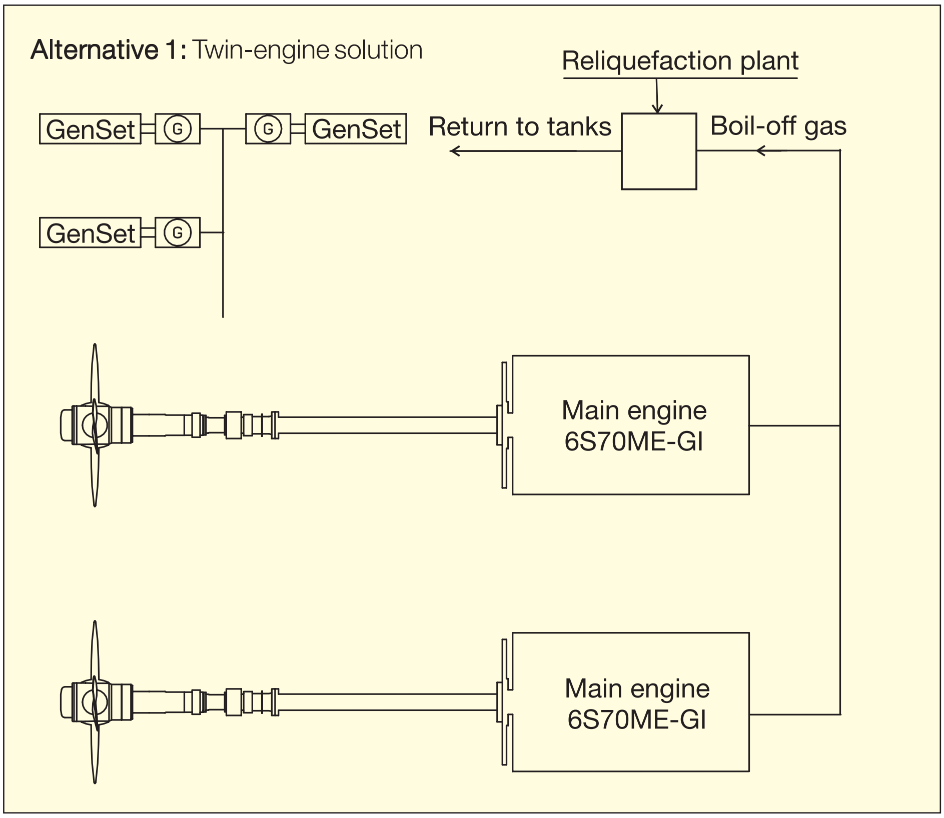

Fig. 13: LNG carrier propulsion systems

Secondary Methods

Water emulsification – NO_x reduction 20-50%

The NO_x reducing mechanism resulting from the introduction of water into the combustion space is a combination of the water reducing the maximum peak temperatures in the combustion process because of its evaporation, and the resulting improved atomisation of the fuel, thereby reducing the NO_x emission.

At the beginning of the 1980s, MAN B&W Diesel made tests on NO_x reduction using water-in-fuel emulsions. Before that time the emulsifier was mostly considered for homogenising of fuel oil to disperse sludge and water remaining in the fuel after centrifuging.

With regard to NO_x emissions, water emulsions showed a significant reduction in NO_x emission with a relatively limited penalty in terms of fuel oil consumption.

Since 1984, long-term service experience has been available from a 7L90GSCA power plant engine, operating on 30% water addition, complying with local rules.

Tests have also been carried out on our research engine in Copenhagen (1L42MC) and on the Spanish island of Menorca (10L67GBE-S) with ultrasonic type homogenisers. Furthermore, tests have been made on a 5S60MC engine with nearly 50% water added. These tests and the service results are all satisfactory, both with regard to NO_x reduction and engine performance.

In addition, ultrasonic homogenising systems for stationary plants are used on the island of Guam. The NO_x reduction is approx. 50% with a 50% water amount added, i.e. water constitutes 33.3% of the total volume of fluid injected into the engine.

The experience from the test and later operation fully covers the expectations with regard to NO_x reduction and operation of the units. For the two-stroke engine, we have experienced 10% NO_x reduction for each 10% water added. The water amounts refer to the injected amount of fuel oil, see Fig. 14.

In order to have the optimal spray in the combustion chamber, it is recommended that the water droplets in the fuel oil after emulsification are max. 5 µm. The test results show that this is easily obtained by using the ultrasonic type, whereas for the early mechanical type the size measured was above our recommended limit.

If the engine is to be operated on diesel oil, it may be necessary to add additives to stabilise the media. We have tested this, and also in this case the performance was good. The location of the homogeniser in the fuel oil system is shown in Fig. 15.

The addition of water to the HFO by homogenisation increases the viscosity, as shown in Fig. 15. To keep the viscosity at the engine inlet at 10-15 cSt, max. 20 cSt, it may become necessary to raise the temperature to more than the 150°C which is standard today (max. 170°C at 50% water) and to raise the fuel oil loop pressure.

The external fuel oil pipe system follows the Germanischer Lloyd class 1 pressure. The supply pump pressure can be changed to $\Delta p = 9$ bar instead of the current $\Delta p = 4$ bar.

Internally on the engine a stronger actuator may be needed for the governor, because of the higher fuel oil supply pressure.

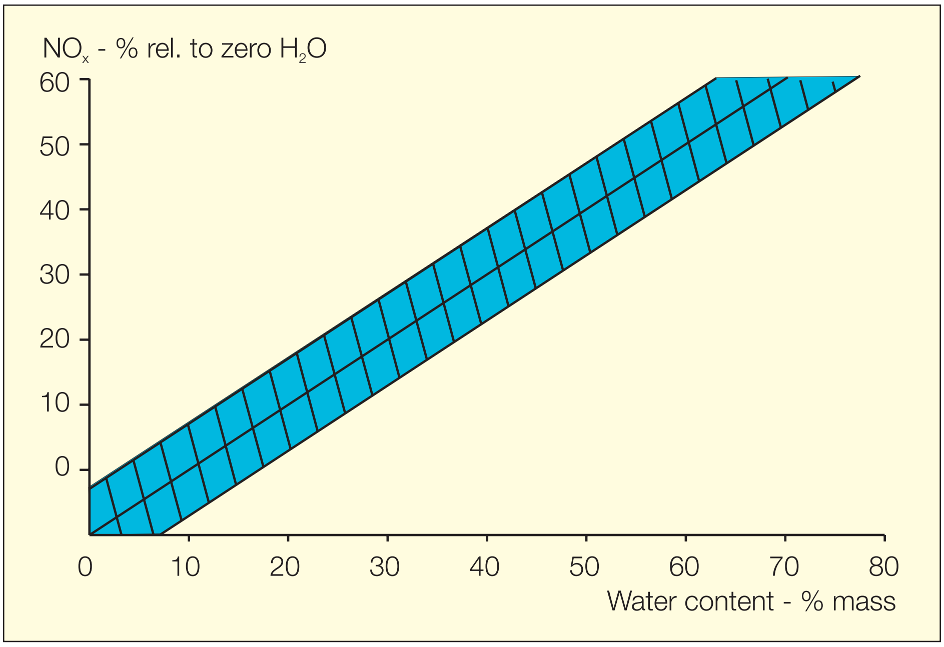

Fig. 14: Typical measured NO_x reductions when using emulsified fuels

The water used for the emulsification has to be distilled. It must comply with the max. limit for fuel for salt (NaCl), as the sodium can react with vanadium in the fuel oil so that particles/deposits of vanadium accumulate on the valve spindles and valve seats, thus resulting in leakages.

The water should be without other salts as well, and be clean so that operation will not result in fouling of injectors and exhaust gas components and boilers.

Therefore, for production of water for the water emulsion, the most obvious source on board ship is the water from the fresh-water generator.

As an example, it can be mentioned that the theoretical amount of water which

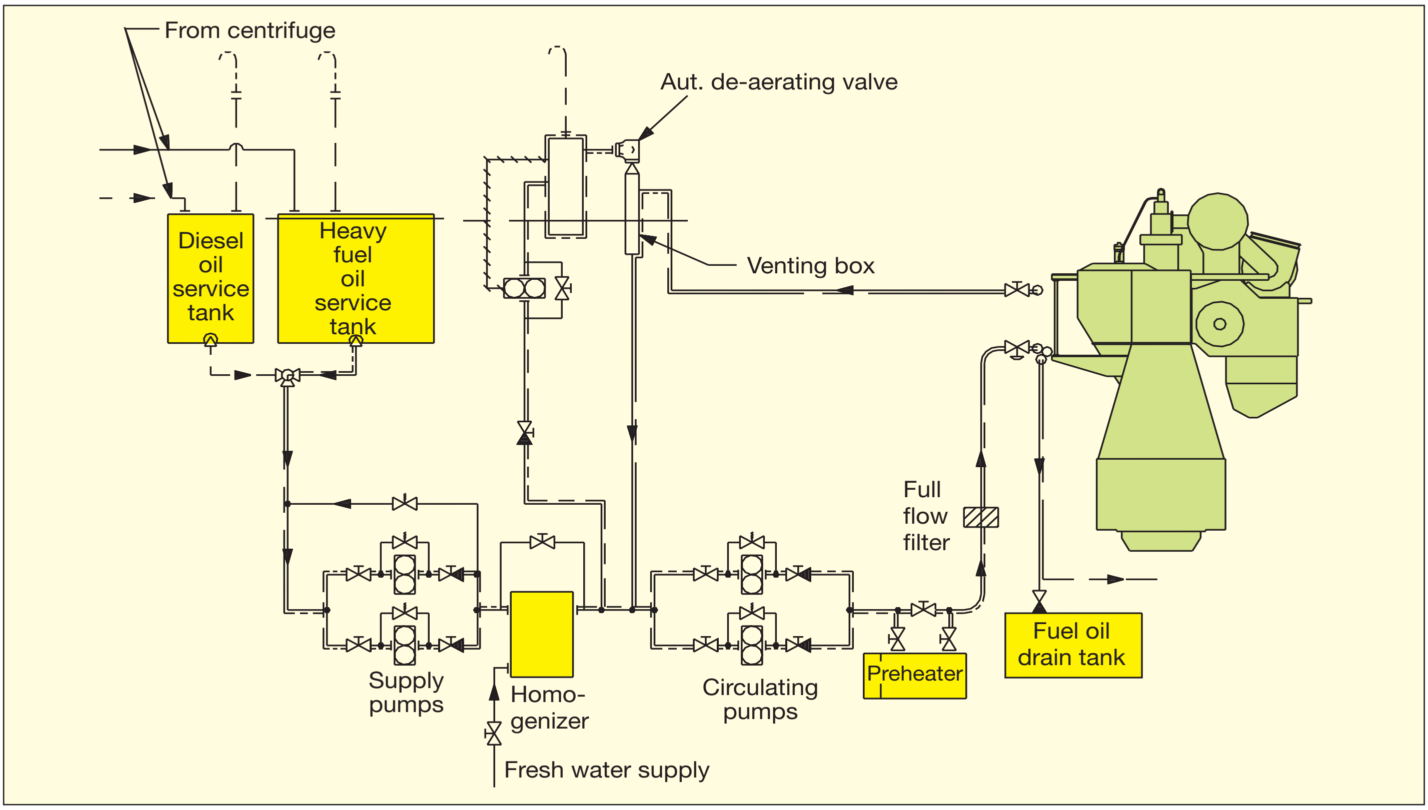

Fig. 15: Pressurised fuel oil system with homogeniser

can be produced by the freshwater generator for an 11K90MC operating at 90% MCR load is about five times more than necessary for 15% water emulsion, and about 2-3 times more than necessary for 33% water emulsion.

Alternatively, the water drained off from the water mist catchers can be used. However, the available amount depends on the humidity in the air.

The homogeniser control system must ensure that the necessary amount of water is added to suit the amount of fuel oil actually supplied.

A micro-processor controls the addition of water so that the fuel/water emulsion always consists of the correct amount of injected water.

A flow meter continuously controls the flow of HFO and water through the homogeniser.

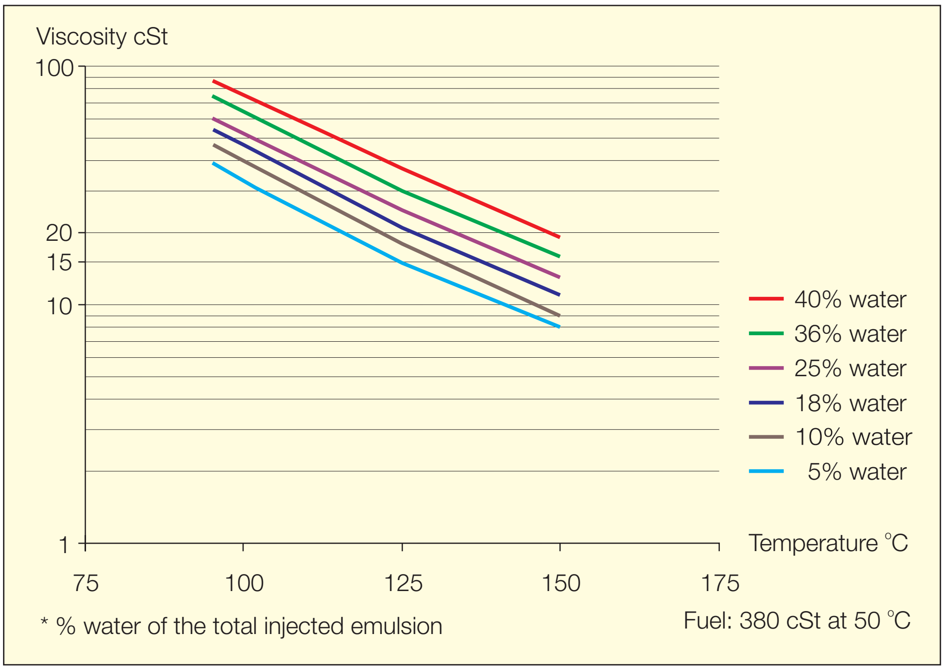

Fig. 16: Viscosity versus water percentage

A safety system to ensure that a change in operation does not influence the stability of the emulsion, and thus the reliability in operation, has been designed and tested by MAN B&W Diesel.

Water emulsification in connection with an electronically controlled engine (ME/ME-C) offers the additional flexibility advantages:

- Optimal injection rate shaping with any water content.
- "Free rate shaping" allows the use of large water amounts even at low engine load as pre-injection can be used to compensate for a larger ignition delay.

Exhaust Gas Recirculation (EGR) and Humid Air Motor (HAM)

Modification of combustion air properties. For both the Exhaust Gas Recirculation (EGR) and the so called Humid Air Motor (HAM) systems, the NO_x reduction effect is achieved by reducing the local maximum combustion temperatures in the combustion chamber, and reducing the concentration of oxygen by the addition of inert media with high specific heat: exhaust gas or water vapour. The NO_x production only takes place at very high temperatures (2,200°K and above), and it increases exponentially with the temperature. The EGR method is based on a reduction of the oxygen content in the cylinder charge, and the HAM method is partly based on reducing the oxygen content of the cylinder charge and partly on increasing the heat capacity of the cylinder charge by the addition of water vapour.

As mentioned above, these methods (EGR and HAM) have, by calculations and tests, proved their capability for NO_x reduction, but they have never before been developed to a commercial application level for large two-stroke engines, and they have not been fully optimised with regard to cross-over effects on fuel oil consumption, heat load conditions and other emission parameters.

After careful evaluation of the EGR and HAM methods, we concluded that recirculation on the high-pressure side from the exhaust receiver to somewhere in the scavenge air system after the turbocharger compressor, with assistance from an EGR blower, would be the most suitable EGR solution. Furthermore, high-pressure side water spray humidification would be the most suitable HAM solution for our two-stroke engines.

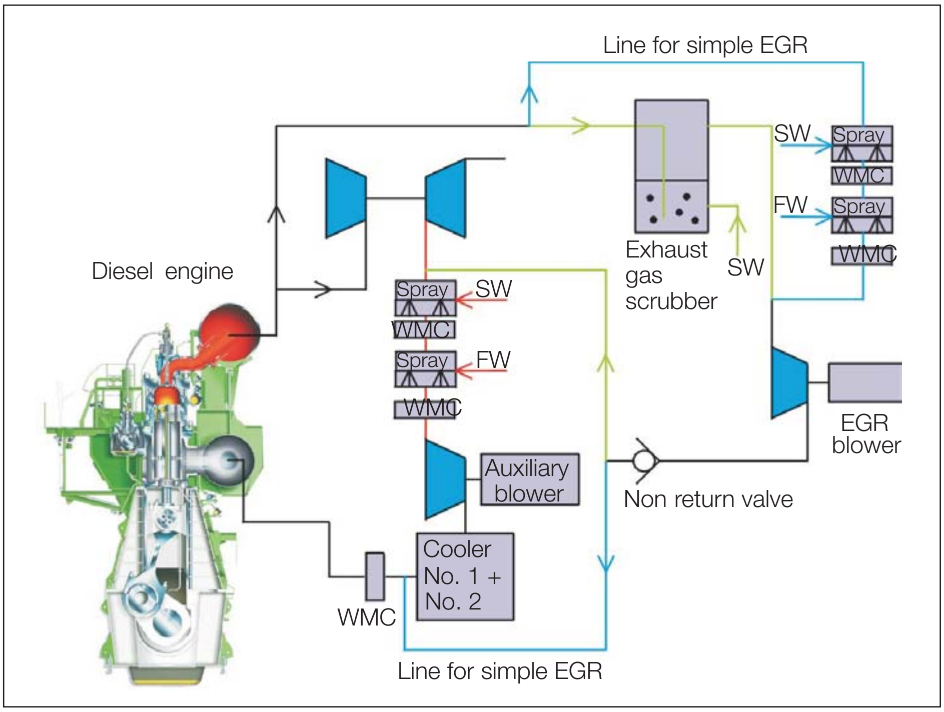

Fig. 17: Schematic design of EGR and HAM systems application on the 4T50ME-X engine

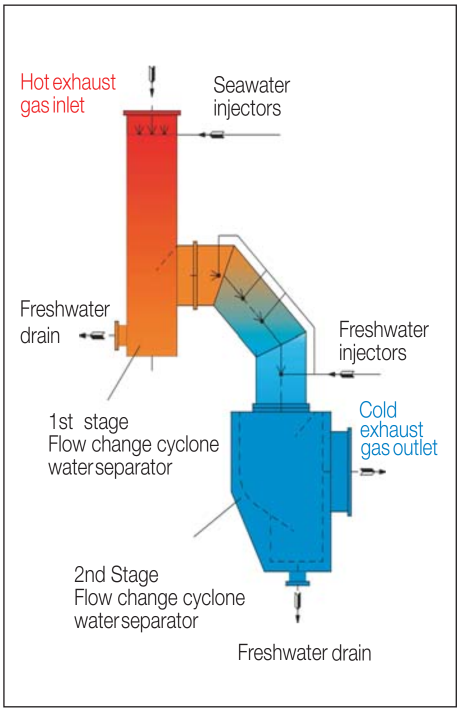

Fig. 18: Design principle of the simple EGR unit

EGR and HAM system designs and component description

Figure 17 gives a schematic overview of the system.

A number of EGR/HAM system configurations, as illustrated in Fig. 17, will be outlined in the following.

Simple Exhaust Gas Recirculation (EGR) (green line, Fig. 17). The purpose of this basic high-pressure EGR system is to test the performance of the simplest possible set-up. This EGR system consists of a gas line from the exhaust gas receiver to a position just after the last charge air cooler, but before the last water mist catcher, so that the risk of fouling of sensitive parts is completely avoided.

In the EGR line, the simple EGR system has two water injection stages, with a simple water separator unit after both, see Fig. 18. The first water injection stage involves humidification with salt water in order to ensure that there is no freshwater consumption in the second freshwater injection stage. The outlet temperature of the first stage is approximately 100°C. This stage has a single multi-nozzle injector.

EGR with scrubber and water treatment
When/if there is a demand for clean EGR gas and/or water outlet from the EGR loop, a more advanced system is required.

This system is connected to the exhaust system in the same way as the simple EGR system, but the EGR line is routed to a "bubble-bath" scrubber from the Canadian company DME (EcoSilencer, ref. Fig. 19), which cleans and cools the exhaust gas.

The water loop in the scrubber system is cooled and monitored in a Water Treatment Skid from DME (ref. Fig. 19) with a filter and settling system, cleaning the used sea water.

Combustion air humidification (Humid Air Motor – HAM) (red line Fig. 17). With this system, the engine runs with saturated scavenge air at higher temperatures than a standard engine, because the conventional inter-cooling is replaced by water spray evaporation/cooling, just after the TC compressor, until the wet-bulb or lower temperature for the hot compressor outlet air is reached.

If/when a scavenge air temperature of approx. 70 °C is acceptable, no conventional scavenge air cooler is necessary, and only a relatively simple spray humidifier system is required.

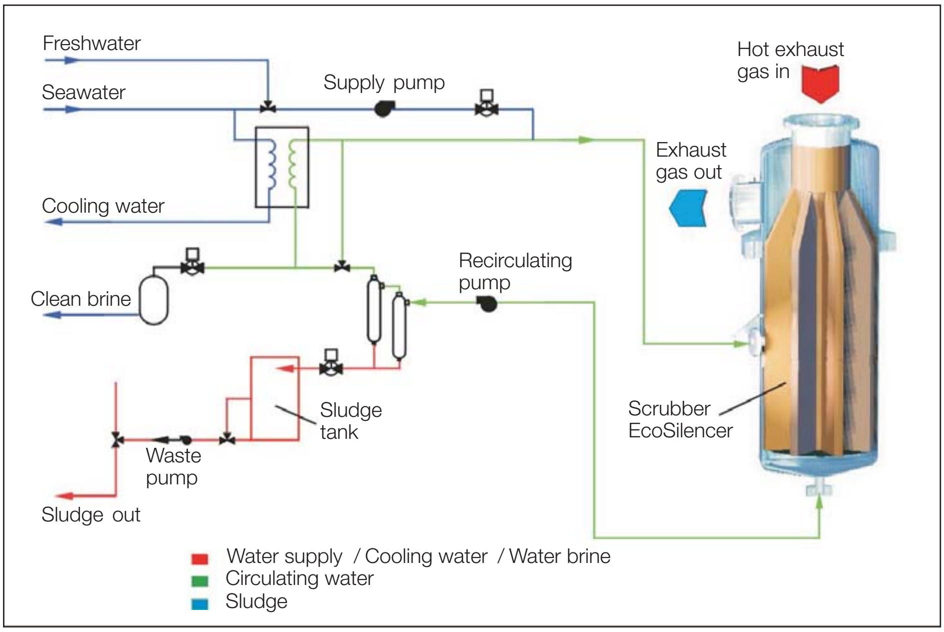

Fig. 19: "Bubble-bath" scrubber (EcoSilencer) and Water Treatment Skid from DME

Results from engine testing with EGR systems

Very promising operating conditions have been obtained during the tests, as outlined in the below summary of the main results.

Emission results. The relative changes in measured emission parameters as a function of the recirculation amount at 75% engine load are illustrated in Fig. 20. As can be seen, at increased recirculation amounts, the HC and PM emissions are reduced corresponding to the reduction of the exhaust gas flow from the engine.

This indicates that each engine cycle has the same production of HC and PM independent of the recirculation amount, and that the HC and PM in the recirculation gas is eliminated during the normal combustion process.

The increase in CO emissions with increased recirculation amount indicates, as expected, that the lower cylinder excess air ratios at increased recirculation amount result in larger local regions in the combustion chamber with lack of oxygen. Furthermore, the expected significant reduction of the NO_x level has been confirmed.

Cleaning the exhaust gas with scrubber. As mentioned in the description of the EGR system, the EcoSilencer has been introduced in the EGR system to clean the exhaust gas and, if possible, also to reduce some of the emission components. MAN B&W Diesel has accordingly measured the emission components at inlet and outlet of the scrubber at different engine loads.

The results from these measurements indicate that scrubbing reduces PM emission to 20-25% (highest at low loads and lowest at high loads) and that HC and CO pass the scrubber nearly unaffected. The NO_2 fraction of the NO_x is, as expected, dissolved in the water, and the NO fraction of the NO_x passes the scrubber nearly unaffected. Fig. 21 shows a picture of the filters used for dilution tunnel PM measurements taken before and after the scrubber at 75% load and 15% recirculation.

Results from engine testing with HAM systems

As for the EGR system also for the HAM system very promising operating conditions have been obtained, as outlined in the following.

Emission results. The measured emission parameters, as a function of the HAM level at 100% engine load, are illustrated in Fig. 22. As can be noted, the HC and PM emissions are nearly unaffected by the HAM level. The CO emissions increase significantly with increased HAM level, most likely due to the lower cylinder excess air ratios at increased HAM levels, which result in larger local regions in the combustion chamber with lack of oxygen. Furthermore, the expected significant reduction of the NO_x level has been confirmed.

NO_x reduction up to 98% when using SCR

To reduce the NO_x level by up to 98%, it is necessary to make use of the SCR (Selective Catalytic Reduction) technique.

With this method, the exhaust gas is mixed with ammonia NH_3 or urea (as NH_3 carrier) before passing through a layer of a special catalyst at a temperature between 300 and 400°C, whereby NO_x is reduced to N_2 and H_2O.

The reactions are, in principle, the following:

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

NO_x reduction by means of SCR can only take place in the mentioned temperature window, because if the temperature is too high, NH_3 will burn rather than react with the NO/NO_2. At too low a temperature, the reaction rate would be too low, and condensation of ammonium sulphates would destroy the catalyst.

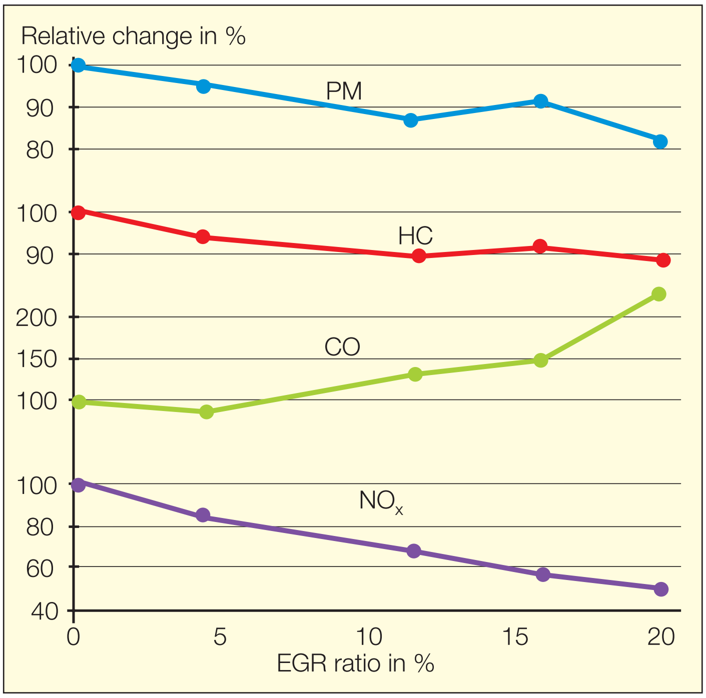

Fig. 20: Emission parameters at 75% load at various EGR ratios

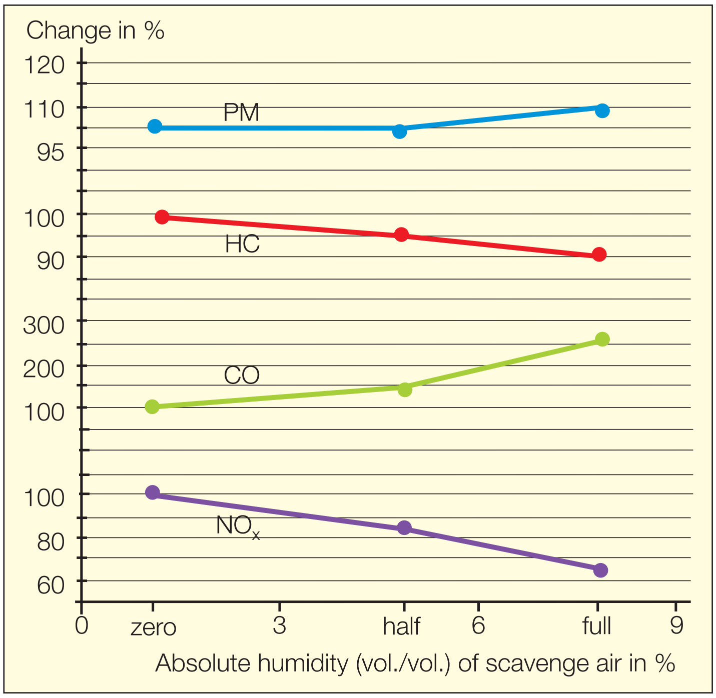

Fig. 22: Emission parameters at 100% load as a function of scavenge air humidity

Fig. 21: PM on filters before and after scrubber

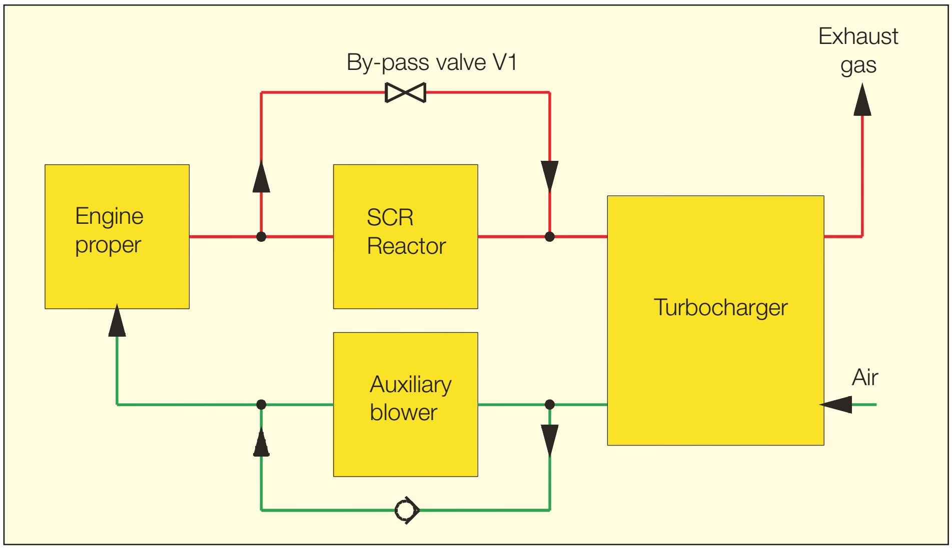

Fig. 23: SCR flow chart

The amount of NH_3 injected into the exhaust gas is controlled by a process computer dosing the NH_3 in proportion to the NO_x produced by the engine as a function of the engine load. The relationship between the NO_x produced and the engine load is measured during test runs on the engine testbed. The relationship obtained is programmed into the process computer and used for the feed-forward control of the NH_3 dosage. The ammonia dosage is subsequently adjusted for bias by a feed-back system on the basis of the measured NO_x outlet signal.

The catalyst has a monolithic structure, which means that it consists of blocks of catalyst with a large number of parallel channels, the walls of which are catalytically active. The channel diameter has an influence on the pressure drop across the catalyst as well as on the risk of deposits on the catalyst. The channel diameter is optimised according to the dust content, the composition of the exhaust gas, and the permissible pressure drop across the SCR reactor.

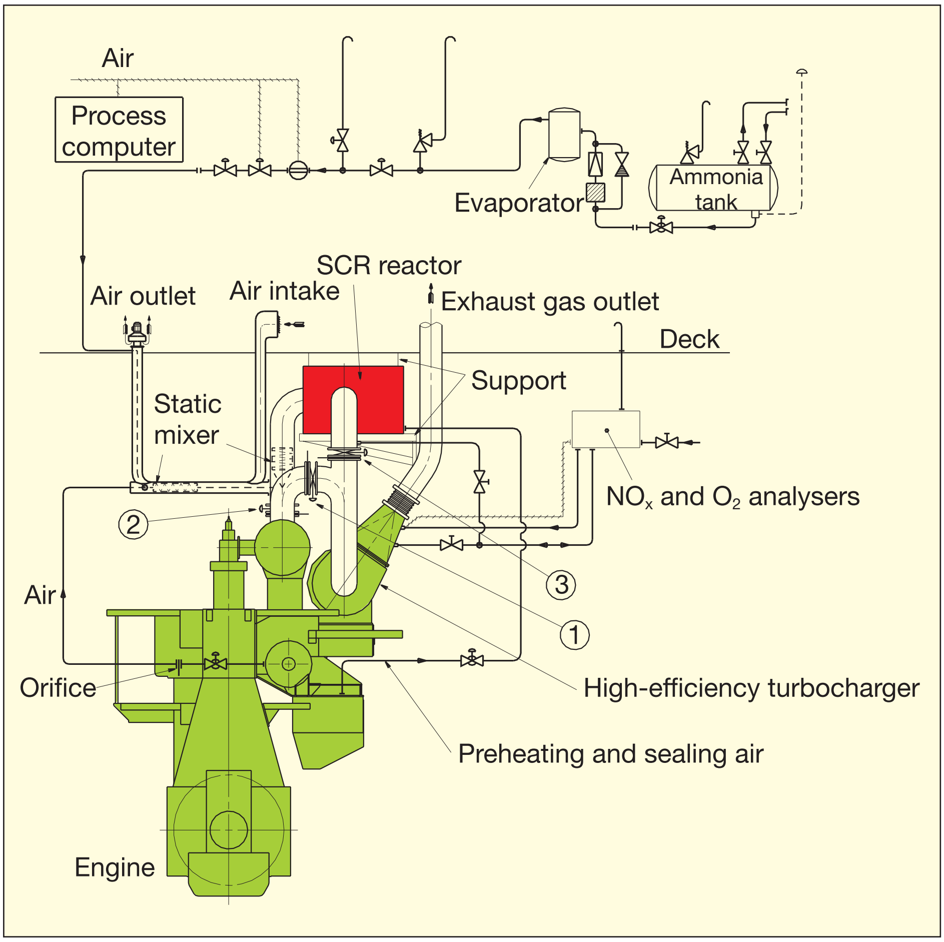

Fig. 24: SCR system layout

1	6S50MC	ship	NO_x reduction	93-95%
2	6S50MC	ship	NO_x reduction	93-95%
3	6S50MC	ship	NO_x reduction	93-95%
4	6S50MC	ship	NO_x reduction	93-95%
5	9K80MC-GI-S	power plant	NO_x reduction up to	98%
6	4L35MC-S	power plant	NO_x reduction	> 93%
7	2x7K60MC-S	power plant	NO_x reduction	> 93%
8	6S35MC	ship	NO_x reduction	> 93%

Fig. 25: SCR reference list for MC engines

In collaboration with the Danish chemical engineering company of Haldor Topsøe A/S, MAN B&W Diesel has developed this method – well known from industrial applications – for use on diesel engines.

Four vessels with 6S50MC engines were equipped with SCR catalysts for NO_x reduction of 93-95%. The first ship was commissioned in 1989 and the last ship in 1994. The systems installed are used when the vessels in regular trade are in the San Francisco Bay area. The systems have performed to specification ever since installed. No reduction in efficiency due to use or ageing is reported. Fig. 23 shows the SCR flow chart, and Fig. 24 the actual system layout on the 6S50MC. Fig. 25 is the current reference list.

High-efficiency turbochargers have to be used. The exhaust gas temperature measured is slightly higher than for engines without SCR because of the ammonia/urea heat release in the SCR process.

The SCR reactor is designed as a semi-rectangular pressure vessel for horizontal or vertical installation and flow. As an example, the following main dimensions (excl. support structure and insulation) are for an 11K90MC engine:

Diameter, m	: 2.4
Height, m	: 4.5
Length, m	: 15
Weight, incl. catalyst, tons	: 42

The design and dimensions of an SCR reactor are influenced by the exhaust gas flow, the exhaust gas temperature window, and the NO_x reduction rate.

The optimum, and most common solution, therefore, is that the SCR reactor is tailor-made for a specific installation and it is, of course, more convenient to build-in the SCR during the construction of the ship. Retrofit is also possible, though.

The space requirement for an SCR unit in the engine room is considerable, on top of which the piping and the mixer between the engine and the SCR catalyst also require a lot of space, so the designer's task is to make the SCR system as compact as possible while, at the same time, ensuring easy access for maintenance and operation.

As can be seen in Fig. 26, we have examined a number of alternative designs of SCR reactors.

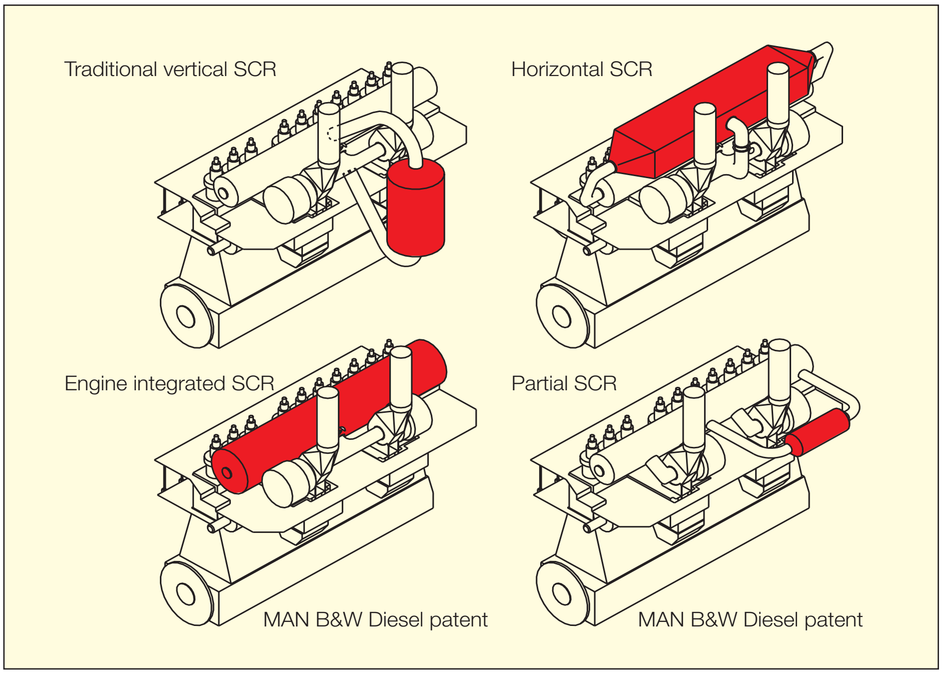

Fig. 26: Alternative SCR configurations

If ammonia is used as the medium for deNO_x, the tank should be located on deck. In the case of urea, we recommend that a tank within the hull structure be used, to lower the cost. Having such a tank in the hull will also minimise the space requirements, compared with the installation of a tank on deck.

If it is not possible to find an appropriate tank on board, the tank could be built into containers.

We have been discussing the issue with Lloyd's and ABS, and it is fully acceptable to use and build-in the tank for urea as outlined.

On the vessel shown in Fig. 27, the *Delta Pride,* the medium is ammonia NH_3, and the supply system and tank are located on deck in a confined space which is open to the atmosphere.

Fig. 27: M/V Delta Pride, 6S50MC, with selective catalytic reduction

Retrofit Installation of SCR – case story

In December 2000, an order was received for the installation of an SCR unit on the Norwegian owned LPG-carrier *Navion Dania*, equipped with a 6S35MC main engine.

The question of installing an SCR unit on this ship had already been raised in 1999 when the ship was being built and, in order to facilitate the possible later installation, the ship and engine were prepared by Hyundai for this option, i.e. space was made available for the installation of an SCR reactor of the proper dimensions.

The urea storage tank was prepared and, on the engine side, the sizes of turbochargers and auxiliary blowers were laidout for the installation of an SCR unit. For contractual reasons, the ship had to continue its operations, so the major part of the installation work was carried out while the ship was in operation.

	Prior to installation of SCR	DeNO$_x$ mode with injection of urea
Engine load	75.8%	77%
Turbocharger rpm	15,600	15,700
T/C inlet temperature	440 °C	440 °C
Scavenge air pressure	2.02 barg	2.10 barg
NO$_x$ emission	1100 ppm*	132 ppm* (<2 g/kWh)
Urea consumption	-	62 l/h

* Measured during SCR test trial

Fig. 28: Engine performance data

opening and late injection timing is possible and, furthermore, modulated exhaust valve timing stabilises the turbocharger.

Hence, ME/ME-C engines and SCR systems are very compatible.

On the *M/V Navion Dania*, urea is used for NO$_x$ reduction. The urea is stored in hull tanks.

The SCR installation work that, normally, would require off-hire was performed during the scheduled guarantee inspections of the vessel.

The SCR test trial was completed in July 2001, and the vessel has since then been operating with reduced NO$_x$ emission from the main engine.

The reduction of NO$_x$ emission for the 6S35MC can be obtained between 40-100% engine load, when running on HFO with a sulphur content of up to 2.4%. Below 40% engine load, the injection of urea is stopped due to low exhaust gas temperatures. The risk of creation of ammonia-sulphate is thereby avoided. Performance data are shown in Fig. 28, and the actual system layout is shown in Fig. 29.

SCR installation on an electronically controlled engine. As for NO$_x$ reduction by means of water emulsion, the flexibility of the electronically controlled engine will improve the emission control and operation.

When operating with an SCR catalyst, it is difficult to maintain the engine dynamics and the turbocharger stability at transient engine loads. However, with the electronically controlled engine, a faster load-up by early exhaust valve

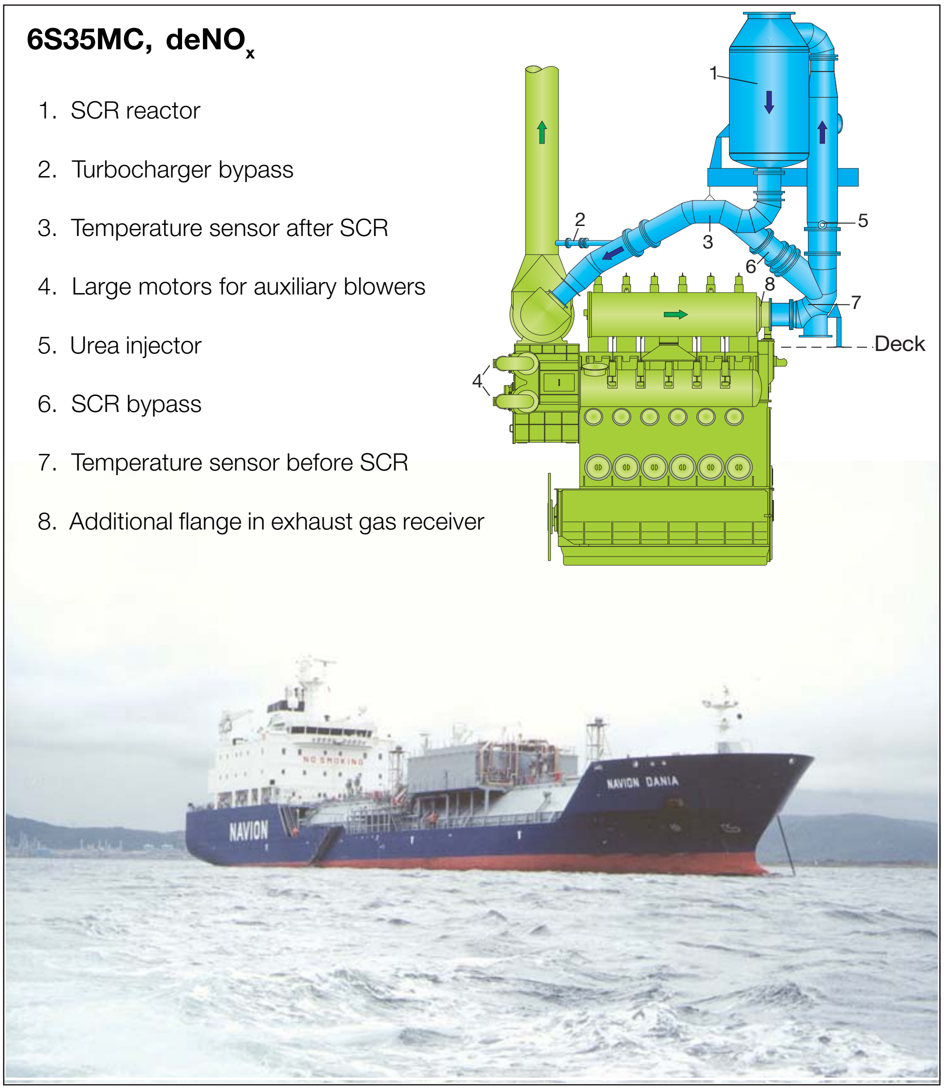

Fig. 29: M/V Navion Dania with SCR catalytic reactor installed

Local Marine Emission Rules

On 19 May 2004, 15 countries representing more than 50% of tonnage in IMO had ratified IMO Annex VI, which will come into force on 19 May 2005.

Countries like Sweden and Norway have introduced reductions in harbour fees for ships operating on low sulphur fuel and with a low NO_x level, in order to encourage low pollution applications. A similar scheme has been introduced in Hamburg.

We foresee more local rules like these coming up, especially if IMO further prolong the ratification period and enforcement date for new IMO regulations.

European Union
The EU is in the process of deciding on which restriction limits to follow. According to the Danish Ministry of the Environment and Energy, the EU is in favour of adopting the IMO Marpol convention, and thus expand the low-sulphur restricted area to include also the French coast in the English Channel, and the North Sea.

Status: Awaiting ratification of the IMO Annex VI.

Sweden
The Swedish authorities decided to aim at a 75% emission reduction by the beginning of 2000. In order to reach this goal, the authorities apply financial incentives in the form of environmentally differentiated fairway and port dues. Reduced dues primarily stimulate the ferry traffic and other maritime traffic to and from Sweden, regardless of the ship's flag state, to take measures which would benefit the environment, such as using catalytic converters or making other technical improvements that decrease the nitrogen oxide emissions and promote the use of low-sulphur bunker fuel.

The environmental differentiation means that the ship-based portion of the fairway dues is differentiated according to the ship-generated emissions of nitrogen oxides and sulphur.

Basically, the authorities give a rebate on port dues when a ship reduces the emission level. As an example, a ship will be given an additional rebate of SEK 0.90 per unit of the ship's gross tonnage if the sulphur content of the bunker fuel is lower than 0.5 mass percent for passenger ships, and 1.0 mass percent for other ships.

These environmentally differentiated fairway and port dues came into force on 1 January 1998.

Norway
The Norwegian Maritime Directorate issues guidelines on emission limits. The limits do not apply to all ship types and are based on a calculation of the total emission load factors from NO_X, SO_X, the type of fuel, and the use of redundant machinery. The higher the emission factor, the better the protection of the environment, and the less is to be paid in tonnage tax by Norwegian owners and operators. This rule became effective on 28 November 2000, and applies to ships above 1000 net register tons.

New EPA emission rules
Tier 1
Valid for all marine engines larger than 30 litres (category-3 engines).

Valid only for US flag ships built after 1 January 2004, and for existing ships which have had new engines installed.

The NO_x emission level is in accordance with the IMO Annex VI speed curve. EPA will issue certificates, Marine Classification Societies or Survey Societies will not be authorized to do so.

In Tier 1, there are no limitations on CO, CO_2, HC, particulate and smoke.

EPA does not set sulphur limits in Tier 1, however, EPA is planning to designate part of the US coastline as a low-sulphur restricted area once the IMO Annex VI has been enforced.

EPA has adopted the IMO compliance rules with only minor exceptions, i.e. the technical file and survey programme, however, minor additional work is necessary, incl. an operation manual.

The manufacturer is responsible for demonstrating that the engine can meet the emissions standards throughout its useful life which, in EPA terms, corresponds to three years, or 10,000 hours of operation, and which may not be less than any mechanical warranty that the manufacturers offer for the engine (extended guarantee and subcon engines).

Manufacturers must include a deterioration factor for emission control components throughout the engine's useful life (three years).

Tier 2
Tier 2 is the next step to be adopted no later than 27 April 2007, with a state of technology that may permit deeper emission reduction. This may also apply to non-US flag ships.

An approx. 30% reduction below IMO Annex VI NO_x limits is being considered. In Tier 2, limits to emissions like SO_x HC, CO and particulates are expected.

Unified Technical File

MAN B&W Diesel has, since the publication of the IMO Technical Code in 1997, worked together with the licensees and classification societies (representatives for flag states) to find a uniform design of the technical files (TF) required under IMO's Annex VI in order to survey compliance on board.

The technical file being the technical test trial's documentation for a specific engine or engine family.

Many of the first TFs produced by the engine builders were based on different demands made by the different classification societies and, therefore, they were not consistent. Basically, this is because the IMO Annex VI does not give sufficiently detailed instructions on how to draw-up the TF in practice.

As a licensor, MAN B&W Diesel has as such assumed the task of coordinating the work to prepare a uniform TF to be used both by the licensees and the classification societies. The task includes the necessary procedures for ship owners, if later engine adjustment or changes of components become necessary.

The advantages of using the unified MAN B&W Diesel TF are as follows:

- Certainty of market acceptance of the TF
- Satisfied customers who are able to show engine compliance when checked at sea by the flag state
- A survey method based on principles familiar to the crew onboard
- More engines can be accepted within the same groups, thus resulting in reduced expenses
- Less money spent on emission measurements
- Parent engines can be shared between MAN B&W licensees, which will greatly reduce the number of emission measurements and future certification costs.

Design of Technical File

The principle of the MAN B&W Diesel unified concept is that the performance data (i.e. measurements of p_{max}, p_{comp}, p_{scav}, T_{scav} and p_{back}) can show whether an engine complies with the NO_x limit. If the operator has changed components or adjusted the engine, the engine will be out of compliance when the engine is later checked by the flag state for compliance at sea, unless extensive testbed testing is performed to validate these changes.

For current testbed and sea trial compliance tests, this is not a major problem, but the issue will be much more important when the IMO Annex VI is ratified, and focus will be on follow-up at sea, where changes and adjustments will take place.

From time to time, some ship owners contact MAN B&W Diesel about these issues, and some owners have already demanded a unified system in order to avoid working with different TFs, depending on which licensee and classification society were involved in an MAN B&W engine delivery.

At sea, in case a ship owner changes components, this unified system will also allow change of the engine's NO_x components while maintaining IMO compliance.

Summary:

The unified TF is the standard TF introduced by MAN B&W Diesel and accepted by the relevant classification societies' headquarters and introduced to licensees for all future engines built.

Assistance from MAN B&W Diesel

In case of any questions regarding the application of the TF, please contact MAN B&W Diesel, dept. 2110. The detailed description of the survey methods can be found in the TF (Chapter 3 and Appendix B).

Conclusions

The development of new measuring equipment for emission control will continue in the coming years, and especially techniques like HAM and EGR will be further developed and tested. The concern of local authorities will change from focussing on NO_x and SO_x to include also smoke, in particular, and CO_2.

The IMO Annex VI was ratified in 2004 and, thereby, an international exhaust gas emission limit for ships will be introduced, but more local rules may also be introduced.

Local rules that encourage the use of emission cutting means, such as SCR reactors, through harbour fee reductions can become more dominant than today, whereas an international rule is preferred by the industry on the ground that the emission cutting means on board are the same wherever a ship is operating and trading. SCR units are preferably installed during the construction of the vessel, however, as seen on the *Navion Dania*, retrofitting is also possible.

MAN B&W Diesel has introduced a unified technical file for the licensee and the engine builder after acceptance from the relevant headquarters of the classification societies' representing the flag state in connection with the Annex VI emission code.

The challenge to shipowners will increase as vessels are required to have, or be prepared for, emission control equipment. The sulphur content in fuel will have to be reduced, and vessel tank systems will have to be prepared for dual fuel and dual cylinder lube oil systems. In some areas, the operating profile of the ship will have to be adapted to local rules for reduced smoke emission. MAN B&W Diesel A/S makes every effort to facilitate adaptation to emission regulations for engine builders, yards and shipowners, with a view to achieving the global target of a cleaner planet. The latest generation of electronically controlled engines are an integral part of that policy, as is our recommendation for use of two-stroke diesel engines as prime movers for LNG ships instead of steam turbines.

References

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[3] "NO_x Emission Reduction with the Humid Motor Concept", 23rd CIMAC Congress, Hamburg, April 2001.

[4] "Soot Deposits and Fires in Exhaust Gas Boilers", paper published by MAN B&W Diesel A/S, Copenhagen.

[5] "LNG Carrier Propulsion by ME-GI Engines and/or Reliquefaction" Sept. 2003