Exhaust Gas Emission Control Today and Tomorrow

MAN B&W Two-stroke Marine Diesel Engines

MAN Diesel

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Contents:

MAN Diesel • Copenhagen, Denmark

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Abstract

MAN Diesel designs and develops two-stroke engines that comply with the demands and regulations made to the maritime industry, and cooperates with authorities, governments and international organisations on the development of new regulations to fulfil the goal of reducing exhaust gas emissions by realistic methods.The aim is to arrive at methods that are applicable and practical to ship operators, and which will maintain a high level of safety and reliability of the engines.

To prepare for coming regulations, general investigations and extensive research are carried out continuously. As shown in Fig. 1, quite a number of emission control measures have already been developed, and are in use by the industry today.

Emission control has turned into the most important driving force development. Hence, this is an area to which extensive development effort is allocated. This emphasises both NO_x control, SO_x limitation, particulate control and, to an increasing extent, CO_2 emission, the latter reflecting thermal efficiency.

With CO_2 considered a greenhouse gas, 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.

The use of waste heat recovery systems to reduce CO_2 among others, is described in a later chapter.

MAN Diesel is in the process of introducing the advanced methods of internal methods for emission control on MC/MC-C/ME/ME-C engines. New tests have shown that a NO_x reduction of more than 70% is possible by means of exhaust gas recirculation.

Humidification of the engine intake air (by means of SAM) is another method that has shown promising test results.

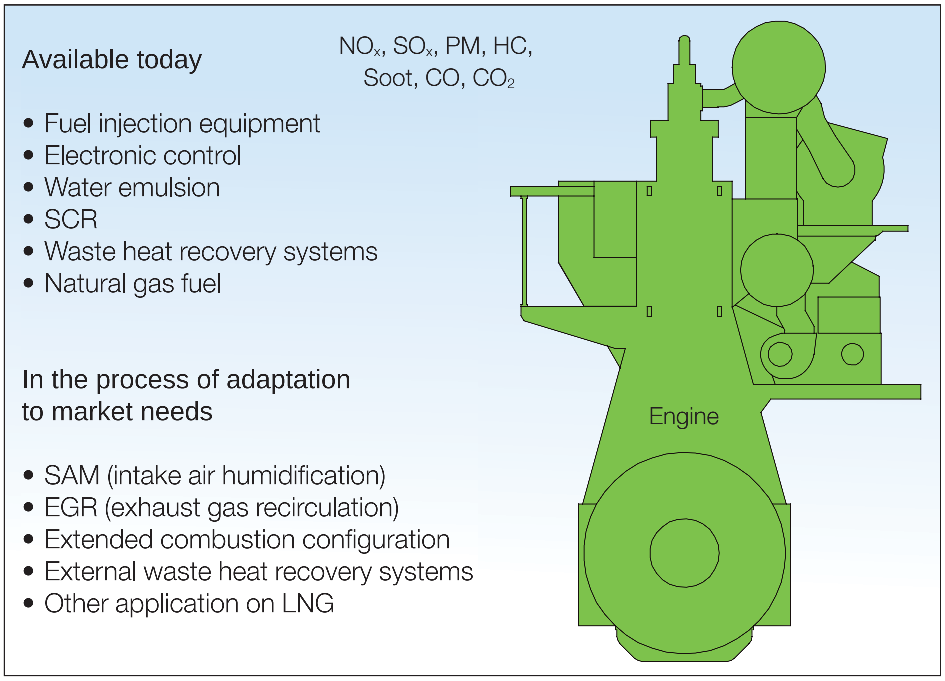
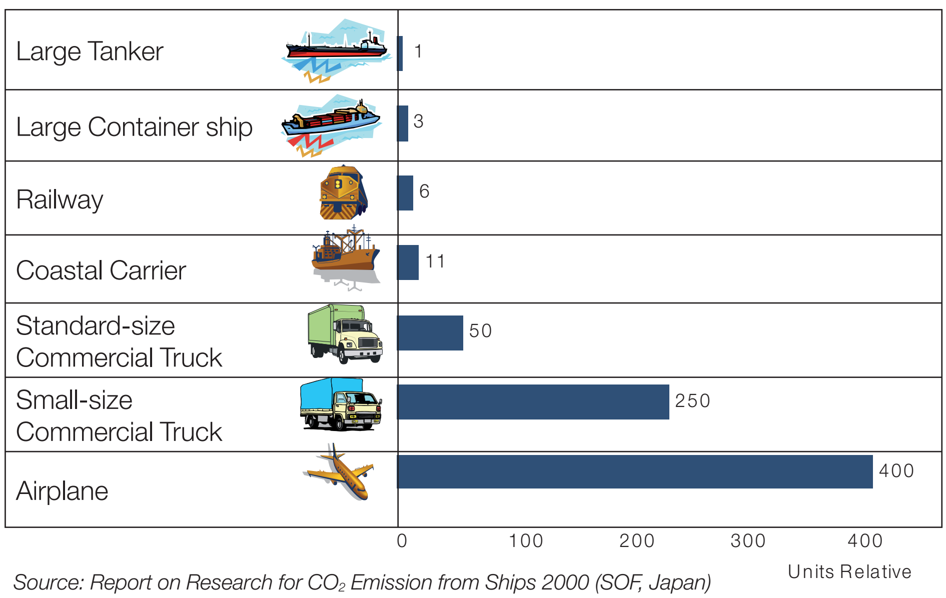


Fig. 1: Emission reduction methods



Source: Report on Research for CO_2 Emission from Ships 2000 (SOF, Japan)
Interim Report by Transport Policy Council 2006 (MLIT, Japan)
Common Guideline for Calculation Method of CO_2 Emission in Logistics (Issued in 2006 by METI and MLIT)

Fig. 2: CO_2 emissions per unit load by transport mode

SAM is currently being tested on a full-scale basis on board a car carrier. As regards CO_2, commercial ships transport approx. 90% of all goods traded worldwide, and still represent by far the most efficient way of transportation, with the lowest production of CO_2 per weight/million moved, as shown in Fig. 2.

However, we still see possibilities of increasing the efficiency by mean of Waste Heat Recovery and achieving a total efficiency of the fuel energy used of up to 60%! This will not only reduce the CO_2 level, but also the amount of emissions of NO_x, SO_x, PM, CO and HC.

Recent advances on our electronically controlled ME engine have shown that the unique rate shaping possibility of ME engines makes it possible to lower NO_x emissions with none or very little effect on fuel efficiency. In this may, the expected NO_x limitations of Tier II will be met by engine internal methods. For the ME/ME-C engine types, the modification, basically, consists in an adjustment of the programming of the electronically controlled injection of the fuel oil.

For the mechanically controlled MC/MC-C engines, the injection equipment and injection timing will be modified

In the 1990s, IMO, EPA and the EU concentrated their work on a reduction of NO_x and SO_x through Tier I. Tier II will continue the focus on lowering NO_x and SO_x emissions, but also such exhaust gas components as particulates, unburned hydrocarbons and CO_2 will be considered for future engine designs and development.

In this paper, the different values for Tier II and Tier III are based on the result of the latest MEPC58 meeting, and the decisions made in May 2008 for the final adoption of revisions of Annex VI and NTC (NO_x Technical Code) on 6-10 October 2008.

MAN Diesel´s Experience and Obligations within Emission Control

Our main obligation as an engine designer is to ensure the highest level of safety and reliability of the equipment installed on ships, while taking into consideration the different types of applications on vessels operating around the world and emission control regulations.

Experience from designing engines, feedback from research conducted on our test facilities, and experience from ships in operation have provided us with the tools to fulfil this obligation and a design basis for emission control methods.

We have researched and designed many emission control techniques to our two-stroke designs and, currently, have water emulsion and SCR in service.

Power plant applications are somewhat easier to adapt to exhaust gas emission control by external equipment because space for external equipment is not limited, and the engines are not operated at changing loads. We have gained valuable experience from using these state-of-the-art emission control technologies on power plants through many years.

Exhaust Gas Emissions from MAN B&W Engines

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.

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.

Once the fuel oil is atomised in the combustion chamber, of a diesel engine the combustion process involves small droplets of fuel oil 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. 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. 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 [1].

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.

Measurements clearly show that the slide-type fuel valve design has quite an impact on HC and particulates.

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. Particularly the higher injection pressure of ME engines at all loads will improve combustion and lower the amount of particulates.

Sulphur content in fuel and particulates in exhaust gas
The sulphur content in fuel oil has a trong impact on the particle level in the exhaust gas. IMO and EU have introduced a restrictions of sulphur of 1.5% in SECA 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 particulate emissions substantially.

Tests and analyses 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.

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, see chapter on low sulphur operation.

Emissions Regulations and Impact on Engine Performance

MAN Diesel has discussed the future state-of-the-art emission control technologies for new as well as for existing engines with the various authorities, and emphasised the potential technical concerns and possibilities in order to assist them in developing their proposals for new emissions regulations.

MAN Diesel believes that the target should be to have international regulations. The regulations on emissions should be accepted for worldwide trading and have internationally-approved special areas such as ECA (emission control area) and SECA, where inland waters and the environment call for further regulation, as is already seen with SECA in the Baltic Sea and North Sea in Europe today. Furthermore, it is very important that the regulations do not dictate which emission control methods should be used, but only specify the levels to be met.

The goal of our research is that internal methods like EGR, WFE, SAM and/or combinations of these will make our two-stroke engines ready for current and future IMO regulations with regard to NO_x, without using SCR with agents such as urea or ammonia. Compared with SCR, which for many years has been considered the optimum solution for NO_x reduction, the new methods have significant advantages that need to be further investigated and matured for the market.

The SCR system is best suited for steady high-load conditions with limited use of fuel oil under defined conditions. Furthermore, SCR is suited for situations where practically all NO_x has to be removed. SCR is less suited for low-load operation and manoeuvring in costal and harbour areas.

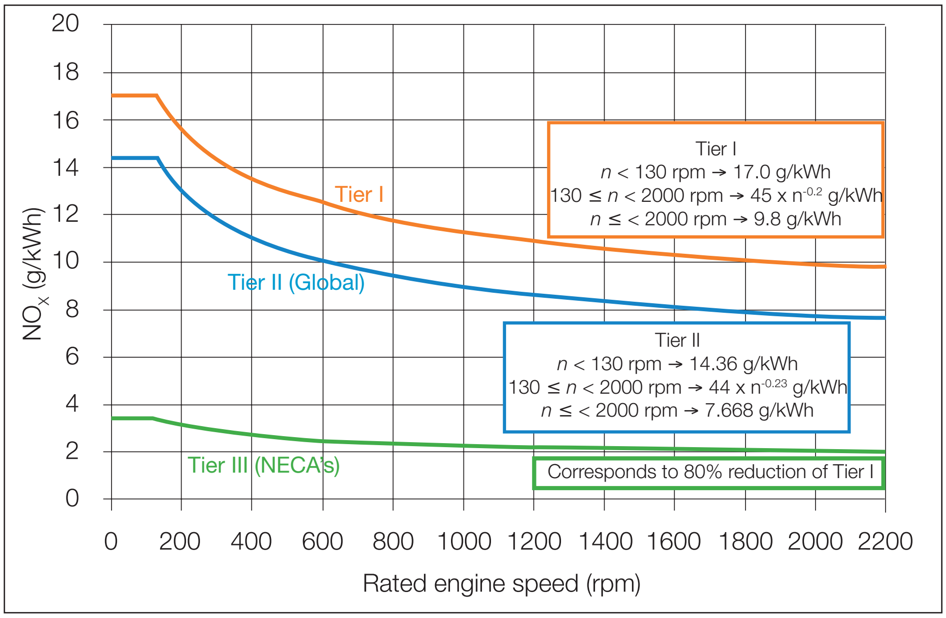


Fig. 3: IMO NO_x limits

New Tier II and Tier III emissions regulations on engine performance
The emissions regulations in Annex VI of MARPOL 73/78 have now been in force since 19 May 2005, retroactive for engines from 1 January 2000, referred to as the Tier I level. At the moment, a review process is progressing to revise the existing emissions regulations and the NO_x Technical Code into a Tier II level.

The regulations are of vital interest to the customers when discussing new orders to be delivered in the relevant time frame.

The decisions on the new limits and regulations have been finalised at the BLG (Bulk, Liquid and Gas) meeting and been approved at the MEPC (Marine Environment Protection Committee) meeting. The scenario and the decisions are outlined in the following.

Tier II, which is to enter into force on 1 January 2011, reduces the existing Tier I level by 2.6 g/kWh NO_x in the relevant speed region for new two-stroke engines, and Tier III, which is to enter into force on 1 January 2016, reduces the existing Tier I level by 80% across the entire speed limit NO_x curve for new engines, but only in a defined local area near shore. Outside this area, the Tier II level will be in force, see Fig. 3.

Furthermore, a regulation for existing pre-year 2000 engines will be introduced, since the contribution of emissions from these engines will exist for still many years to come. The NO_x limit level for these engines will correspond to the Tier I level for new engines as of today. It is anticipated that the certification procedures and the technical documentation needed will be somewhat reduced in comparison to the requirements for new engines in order to make the regulation practicably possible.

With regard to SO_x and PM regulations, this is to be controlled by a limitation in the sulphur content of the fuel used. An alternative measure is the use of scrubbers, see Table I.

Table I: Fuel sulphur limits - implementation dates and use of scrubber

Implementation date	SO_x Emission Control Areas	SO_x Global	Scrubbers
Existing regulation	1.5%	4.5%	Only in ECA´s
1 March 2010	1.0%		Alternative measures (scrubbers) in ECA´s and globally
2012		3.5%	
2015	0.1%		
2018		Review of 2020 fuel situation	
2020		0.5% (HFO allowed) Alternative 0.5% intro date	
2025			

How to meet Tier II
All relevant new engines can be updated by internal methods to meet Tier II.

This can be achieved by introducing new fuel system components like plunger/barrel and fuel valve nozzles, and by an adjustment of the combustion chamber volume by piston rod shims, the scavenge air pressure and the exhaust cam profile, on MC/MC-C engines, and on ME engines the fuel pressure booster and fuel valve nozzle, combustion chamber volume by piston rod shims, the scavenge air pressure and electronic control parameter settings can be adjusted. Furthermore, Inconel cladding and Nimonic exhaust valves will most likely be introduced on some engine types in connection with the Tier II optimisation.

When discussing exhaust gas emissions from ships, it is understandable that focus is on the engine's funnel. The power needed to move the ship at a certain speed is a sum of the hull design and resistance, and the loading of the ship. With a different ship design, or utilisation of a waste heat recovery system, a substantial reduction in emissions can be gained. Using the ME-GI engine is another possibility for reduction of exhaust gas emissions for the large LNG carrier market coming up.

Optimising the emission control is not restricted to the engine only.

Another possibility is to adjust the ship speed. For example, by reducing the speed by 10%, emissions are lowered by 20%. This option could be used close to shore.

In the future, we expect that the fuels used close to shore will be with a reduced sulphur content. The procedure to change between different fuel types is standard when a ship goes for a repair involving the fuel system or is laid up for a longer period. SECA areas have already been introduced by IMO and the EU, and low-sulphur HFO is not expected to be available at all fuel bunkering terminals.

DO and GO will be utilised instead. This means that the operator will have to carry out a change-over between these fuels much more frequently. This is considered a safe operation, but only if the appropriate procedure is followed.

The electronic control of the ME/ME-C engines, or the new ME-B type engines, offers much wider possibilities for emission control. The electronically controlled fuel injection, exhaust gas valve actuation and turbocharger control, as well as combinations with design changes of primarily the combustion chamber components, have shown great possibilities. We have made extensive investigations on the MAN Diesel 4T50ME research engine in Copenhagen to explore the sensitivity of engine parameters against fuel type and physical and thermodynamic conditions on the engine. The study showed a promising trade-off between the engine fuel consumption and the NO_x level. Such studies are now a part of our very promising development work. Results are shown in Figs. x and y.

To give operators a unified technical file to be followed by MAN B&W licensees, a procedure has been developed by MAN Diesel and accepted by the flag state representatives, i.e. the classification societies. The unified technical file is described in a separate chapter. Until now, local rules have been introduced in Sweden, Norway, and the harbour of Hamburg, where for example a harbour-fee reduction is used as an incentive to use 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.

The authorities have so far focused on NO_x and SO_x, but as soon as the IMO Annex VI has been ratified, more attention will be paid 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 type of cylinder lube oil and dosage used are influencing factors.

With regard to lube oil, MAN Diesel has introduced the so-called Alpha Lubricator, which enables the operator to make a considerable reduction in the cylinder lube oil and consumption and, thereby, achieve a reduction in particulate emissions.
With turbo-generator and turbo-compound system plants, the prime mover can be configured to 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.

Tier II impact on main performance parameters

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), as well as injection pressure and profile.

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 the MAN Diesel engine portfolio, this concept is named ME/ME-C and ME-B, comprising a range of low speed engines with most of 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. The ME-B engines have electronic fuel injection timing control, like the ME engines, but at the same time they have a small camshaft for mechanical exhaust valve opening.

The electronic control of fuel injection 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 actuation, 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.

Both ME and ME-B engines benefit from a lower fuel penalty when complying with Tier II, contrary to its mechanical counterparts, due to the possibility of rate shaping.

Reducing NO_x emissions is generally related to an SFOC increase, and our evaluation of the impact on SFOC and other main performance parameters are outlined in Table II.

Table II: Tier II impact on main performance parameters

For MC/MC-C in general:	
SFOC:	up to 6 g/kWh increase at L1 MCR.
Exhaust gas amount:	Nearly unchanged
Exhaust gas temperatures:	Nearly unchanged
For ME/ME-C/ME-B in general:	
SFOC:	up to 4 g/kWh increase at L1 MCR.
Exhaust gas amount:	Nearly unchanged
Exhaust gas temperatures:	Nearly unchanged

Unified Technical File

Since the publication of the IMO Technical Code in 1997, MAN Diesel has, 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 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 shipowners, if later engine adjustment or changes of components become necessary.

The advantages of using the unified MAN 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 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.

A set of performance data taken when the NO_x emission level was measured, and in compliance, serves as the proof of compliance in the future. If derating performance data are revealed, it may be presumed that the engine is out of compliance and in need of readjustment.

If the operator changes components or adjusts 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 has bean 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, shipowners contact MAN 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 shipowner changes components, this unified system will also allow change of the engine's NO_x components while maintaining IMO compliance.

On board continuous emission measurements (CEM) may serve as an alternative to the technical file.

Summary:

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

Assistance from MAN Diesel regarding the application of the TF can be request -ed by contacting MAN Diesel. The detailed description of the survey methods can be found in the TF (Chapter 3, Appendix B).

Emission Control Methods Available Today, Experience and Limitations

Alpha Lubricator

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.

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 lubrication to ensure a satisfactory piston ring/liner wear rate and maintaining, or improving, the time between overhauls.

MAN Diesel has achieved this by developing the Alpha Lubricator system, 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 mechanical lubricators. Both for marine engines and engines for power generation purposes, lower feed rates have been demonstrated.

By applying a low oil dosage, about half of the usual emissions are 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.

Water emulsification

The NO_x reducing mechanism, resulting from the introduction of water into the combustion chamber, is accomplished by the water reducing the peak temperatures in the combustion process.

At the beginning of the 1980s, MAN B&W Diesel carried out NO_x reduction tests 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 power plant engines, operating with up to 50% water addition in order to meet local rules.

Experience with ultrasonic type and mechanical homogenisers has also been gained from the former MAN B&W research engine in Copenhagen

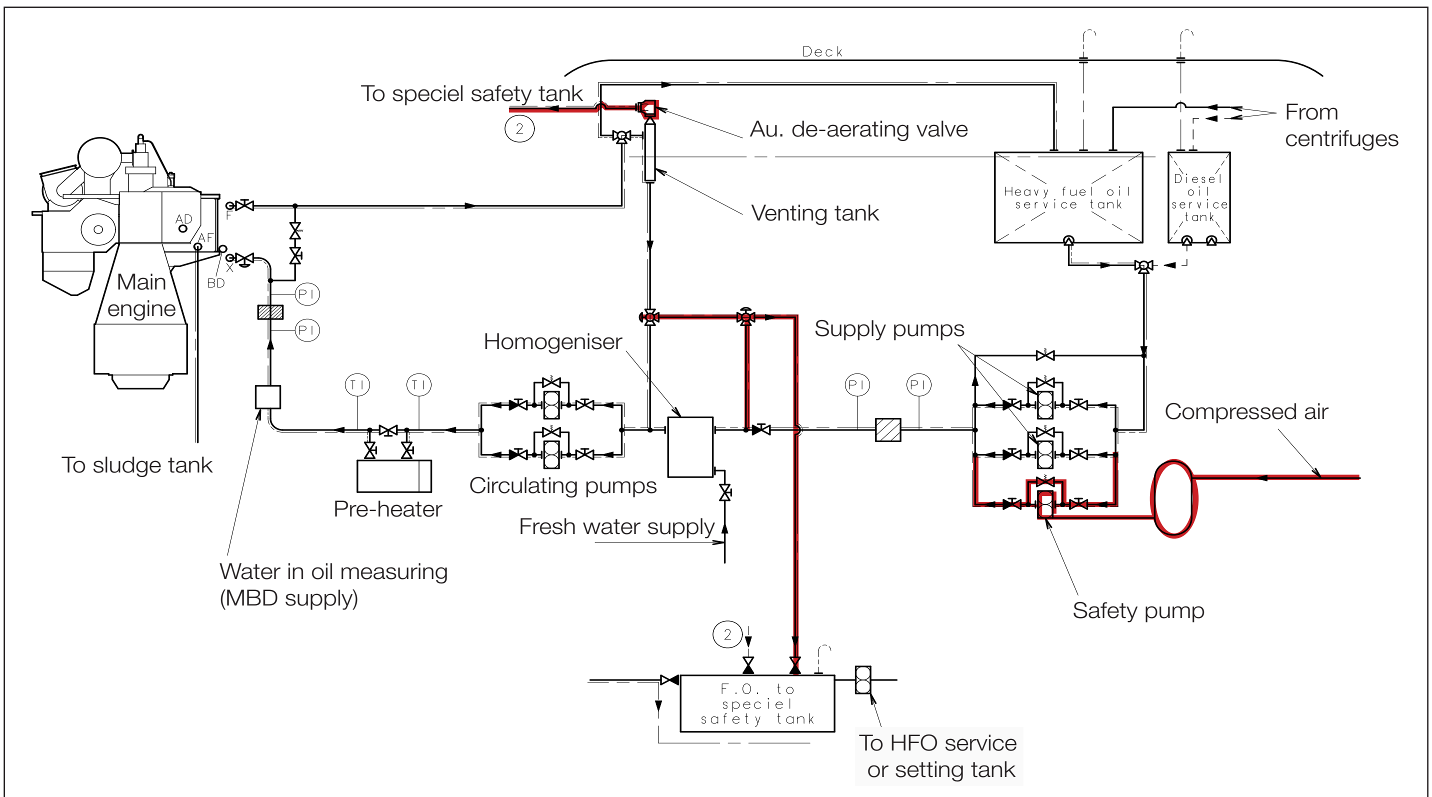


Fig. 4: Pressurised fuel oil system with homogeniser, incl. safety pump and drain tank

(1L42MC) and on the Spanish island of Menorca (10L67GBE-S). 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.

The rather wide variations in load and high safety level required for marine vessels necessitate testing and system approval of the specially designed safety system. Therefore, a full-scale test installation is currently in service on an 11K90MC engine installed on an APL container vessel. The test is expected to be finalised at the beginning of 2009. The experience from the test and later operation fully covers our expectations with regard to NO_x reduction and operation of the units. For the two-stroke engine, we have seen a 10% NO_x reduction for each 10% water added.

Homogenisers for water emulsion

In order to have the optimal spray into the combustion chamber, it is recommended that the water droplets in the fuel oil after emulsification are as small as possible. Both ultrasonic and mechanical types of homogeniser can be used to obtain the same level of NO_x reduction per water unit added without penalising the engine performance.

However, if the engine is to be operated on diesel oil, it may be necessary to add additives to stabilise the emulsion. The location of the homogeniser in the fuel oil system is shown in Fig. 4. The same position is used irrespective of whether the homogeniser type is mechanical, ultrasonic or high-pressure injection.

The addition of water to the HFO by homogenisation increases viscosity. 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, accordingly, to raise the fuel oil loop pressure in order to avoid boiling of water.

The water used for the emulsification has to be demineralised. 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, exhaust gas components and boilers.

It will be necessary to add an air driven safety pump and the drain tank to the system. The air driven pump will keep the system pressurised in the event of black-out. The drain tank is used if the system must be flushed to remove water emulsified fuel. Both systems are patented by MAN Diesel.

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

- Optimal injection rate shaping can be achieved both without and 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 ignition delay.

A high-pressure homogeniser injection system has been tested on the MAN B&W 4T50ME-X research engine in Copenhagen, showing the same NO_x reduction as conventional homogenisers.The high-pressure injection system was in the test compared with the traditional ultrasonic homogeniser.

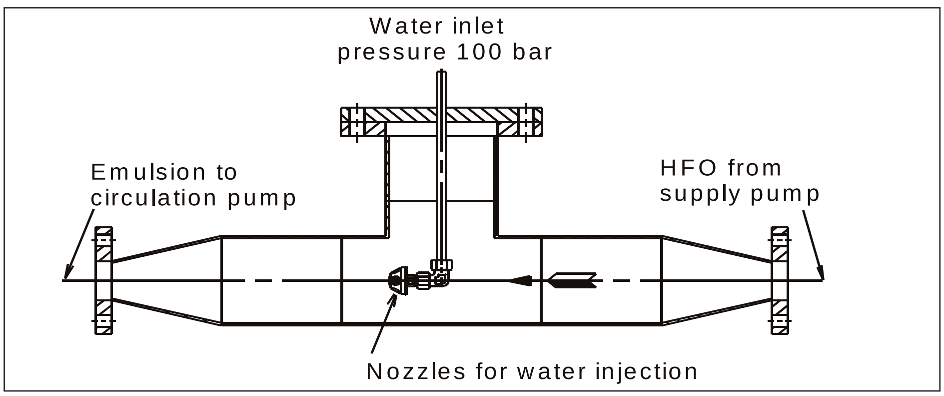


Fig. 5a: High-pressure (100 bar) injection of water in the fuel line

Fig. 5b: Pump unit

The working principle of the high-pressure injection system is water sprayed into the fuel by a special nozzle at 100 bar pressure at the nozzle tip (see Fig. 5).

The high-pressure pump is “frequency controlled”, and can deliver the needed water amount at constant pressure at all times.

SCR

MAN Diesel’s experience with SCR (selective catalytic reduction) for NO_x emission reduction on MAN B&W two-stroke diesel engines for marine application dates back nearly 20 years.

The SCR system is best suited for steady high-load conditions, i.e. SCR is less suited for low load operation and manoeuvring in costal and harbour areas. The sensitivity of the chemistry between cylinder and fuel oil also shows limitations for marine operation.

This is further emphasised by the need to fit the SCR reactor BEFORE the TC due to the required temperature regime.

We have experienced a 98% NO_x reduction on a stationary gas power station during full SCR operation. However, the load profile for marine vessels differs significantly from load profiles for stationary power stations. In this paper, we will concentrate on marine vessels.

Marine experience and challenges with SCR

SCR is the method for NO_x reduction on diesel engines today which can give the largest reductions. As already mentioned, practically all NO_x can be removed. Some complications and limitations, however, make it more difficult to apply SCR on marine vessels in service. This makes it unfeasible to remove more than 90-95% NO_x due to the risk of ammonia slip.

If we compare the SCR installation on new ships to a retrofitted SCR system, it becomes obvious that it is far more complicated to retrofit the installation than to integrate SCR as the ship is being built. First of all, to find the required space for the catalyst, piping, support, auxiliary equipment, and NO_x, O_2, and NH_3 measuring devices is a challenge more easily solved on new ships.

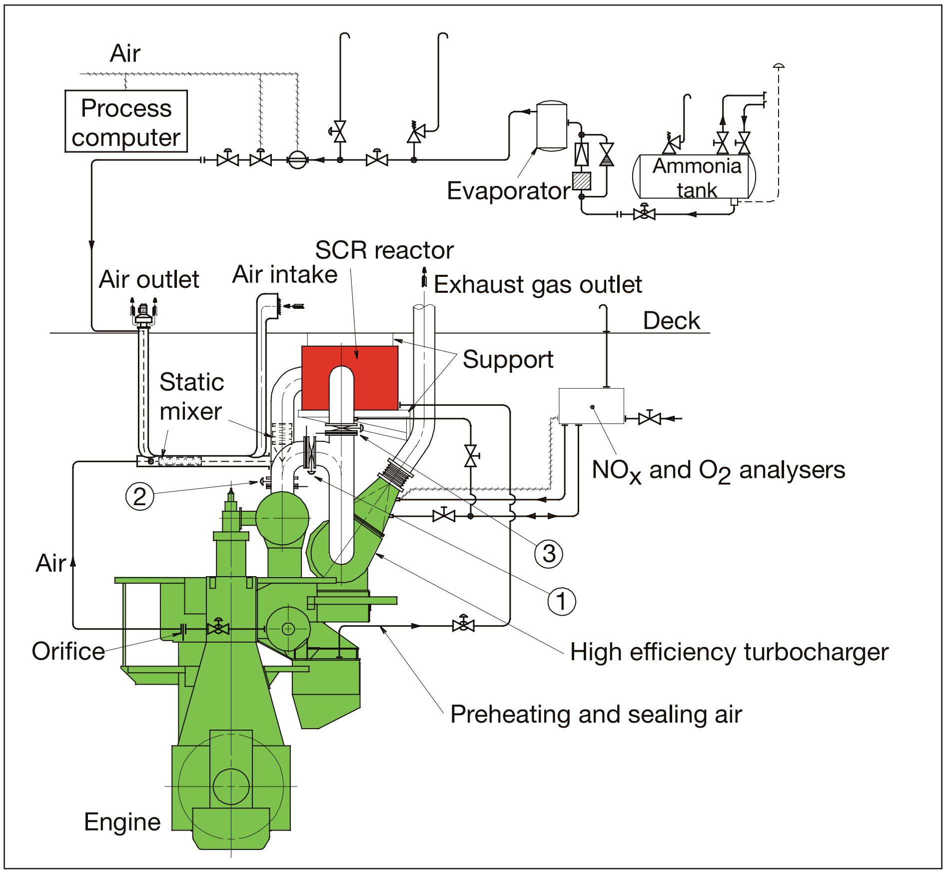


Fig. 7: SCR system layout

Working principle

With the SCR technique, 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:

$$4NO + 4NH_3 + O_2 \longrightarrow 4N_2 + 6H_2O$$

$$6NO_2 + 8NH_3 \longrightarrow 7N_2 + 12H_2O$$

NO_x reduction by means of SCR can only be carried out in this specific temperature window:

- If the temperature is too high, NH_3 will burn rather than react with the NO/NO_2.
- If the temperature is too low, the reaction rate will also be too low, and condensation of ammonium sulphates will destroy the catalyst.

If the temperature limits are violated, the channel diameter is optimised according to the dust content, the composition of the exhaust gas and the permissible pressure drops across the SCR reactor, and the catalyst will block.

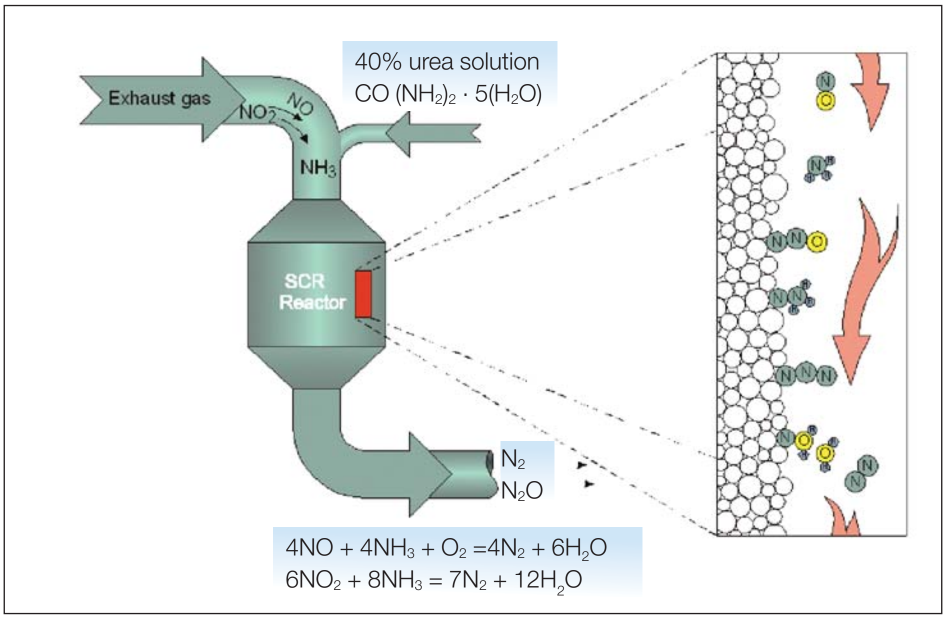


Fig. 8: Selective Catalytic Reduction (SCR) process

Consequently, the SCR system will stop working within hours.

To keep the temperature within the limits, the SCR catalyst must be located between the exhaust gas receiver and the turbocharger, so that the SCR catalyst can sustain the pressure at the turbocharger inlet (i.e. no pressure drop). Due to a high pressure at the inlet the SCR can be reduced in size compared to catalysts on some medium and high speed engines, where the SCR unit is located in the exhaust gas funnel.

A process computer controls the amount of NH_3 injected into the exhaust gas: The correspondence between NO_x and the engine load is measured on the engine testbed. Based on the results from the testbed, the process computer calculates and controls the NH_3 feed rate. The ammonia dosage is subsequently adjusted by a feed-back system based on the measured NO_x outlet signal.

When engine exhaust gas is released from the exhaust gas receiver, urea or ammonia is supplied to the pipeline via double-wall piping into a mixer. The engine exhaust gas is mixed with the agent and led into the turbocharger in the turbine side.

To compensate for the pressure loss across the SCR system, high-efficiency turbochargers and high performing auxiliary blowers are mandatory. Due to the ammonia/urea heat release in the SCR process, the exhaust gas temperature from the turbocharger is slightly higher than the exhaust gas temperature in engines without SCR.

Otherwise, engines with and without SCR show the same performance and heat balance, and so they produce similar service results as regards safety, reliability and availability.

The SCR process is feasible on two-stroke diesel engines with only minor impact on the engine performance, but with restrictions on the engine load, sulphur content, cylinder lube oil, and excess of ammonia (or urea).

The number of SCR systems installed on two-stroke diesel engines is still limited. Therefore, today an SCR system is specially designed for each main en-

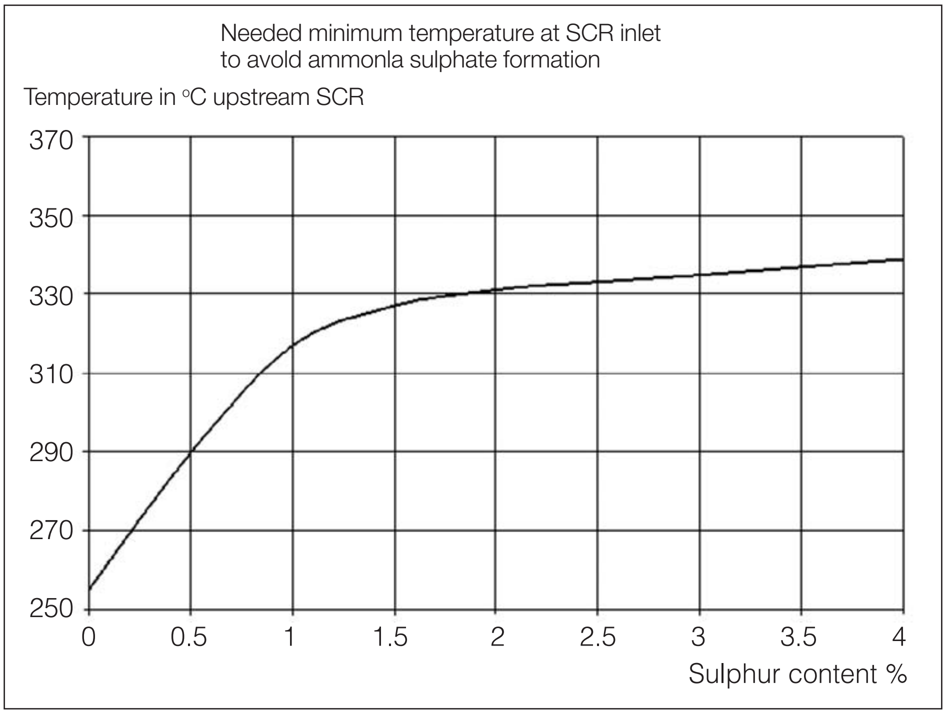


Fig. 9: Minimum temperature for SCR operation

gine. Retrofitting is complicated and not recommendable if the vessel has not been prepared for later SCR installation.

To avoid chemical compositions blocking the SCR, the sulphur content in the fuel oil used on engines with SCR is important as is, in particular, the lower exhaust gas temperature limit at the inlet engine.

Furthermore, some SO_x will be converted to SO_3 in the SCR catalyst and thus create visible smoke.

Calcium from the cylinder lube oil can have an impact, so an excessive cylinder feed rate causing CaSO4 should be avoided.

When installing the SCR catalyst, it is important to compensate the exhaust pipe and the component support for vibrations and temperature changes.

Emission Control Methods Under Test and Maturing for Future Regulations

While it is realised that reduction of NO_x from marine engines will be required to up to 80% and while the complication of SCR is also reduced,

New technology for internal methods of NO_x reduction is currently being developed and is expected to be matured for the market within 3-4 years. MAN Diesel encourages that such techniques like exhaust gas recirculation and scavenge air humidification, and a possible combination of these also with water in fuel emulsification, are investigated further.

For both the exhaust gas recirculation (EGR) and the so-called scavenge air moisturising (SAM) systems, the NO_x reducing effect is achieved by reducing the local maximum combustion temperatures in the combustion chamber, and by reducing the concentration of oxygen, adding inert media with a high specific heat capacity, i.e. exhaust gas CO_2 and 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 SAM 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 SAM) 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 and testing of the EGR and HAM methods, we concluded that re-circulation 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 SAM solution for our two-stroke engines.

SAM system

The SAM system for saturation and cooling of the compressed air from the compressor side of the turbocharger has been tested from an engine performance point of view on the 4T50ME-X research engine. The tests gave promising results with regard to the ability of reducing NO_x emissions. However, long-term influence of the SAM system on engine components as well as operation with a salt content of up to 3.5% could not yet be investigated.

Full-scale test on *M/V Mignon*

Wallenius-Wilhelmsen Lines has allowed a full scale test on their vessel *M/V Mignon* in order to investigate the long-term impact in a marine environment. The *M/V Mignon* is equipped with an 8S60MC engine. The SAM system needed, therefore, to be adapted to the existing engine construction and the installation was further limited by the available space in the engine room.

SAM system on the engine

The SAM system on the 8S60MC engine consists of the arrangement shown in Figs. 9 and 10.

The SAM system has a sea water injection stage, where a surplus of sea water is injected for saturation and cooling of the hot air from the compressor. The sea water stage will provide a near 100% humidification of the scavenge air and supply all of the water for humidification.

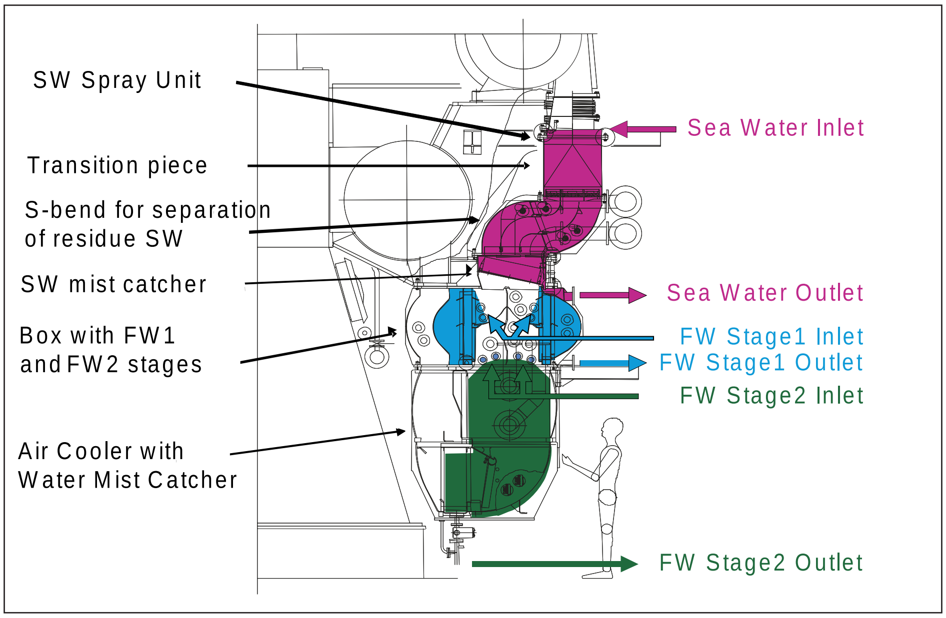


Fig. 9: SAM part on the engine

The freshwater stages 1 and 2 will be near temperature neutral to the scavenge air and create a small freshwater production depending on the operation parameters chosen. The freshwater stages only act as cleaning stages for removal of any salt which may pass with the air from the sea water stage. A continuous accumulation of salt in the freshwater stages would eventually cause the salt content to reach an unacceptably high level. This is counteracted by cooling the saturated air with the air cooler and generating some extra freshwater for stage 2. The extra freshwater is then sent upstream on the tank side of the SAM system, as illustrated in Fig. 13. Thereby the content of salt in the freshwater stages can be controlled.

A vital aspect in ensuring that no or a minimum of salt gets into the engine is a good efficiency of the water drainage. All the water drainage systems are, subsequently, based on the slung principle followed by mechanical water separation in metal foam. Measurements on a small pilot plant has indicated an efficiency as high as 99.6% with this solution. The efficiency of the water drainage for the sea water and fresh water stages is 99% in the example in Fig. 11.

The SAM parts in the compressor air cooler arrangement (i.e. SW spray, transition piece, S-bend and inlet box for FW1 and FW2) are manufactured in austenitic stainless 254SMO because of its excellent resistance against corrosion from salt water.

The additional mass flows provided by the evaporated water for the turbines have the effect that a substantial part of the exhaust gas has to be bypassed in this project. However, the energy of the bypassed exhaust gas could be utilised in a power turbine and provide operational cost savings for the operator as well as a reduction in the overall CO_2 emission. The SAM system is, thereby, a NO_x reduction method with a potential for improvement of the overall efficiency as well.

Fig 10: As built on M/V Mignon

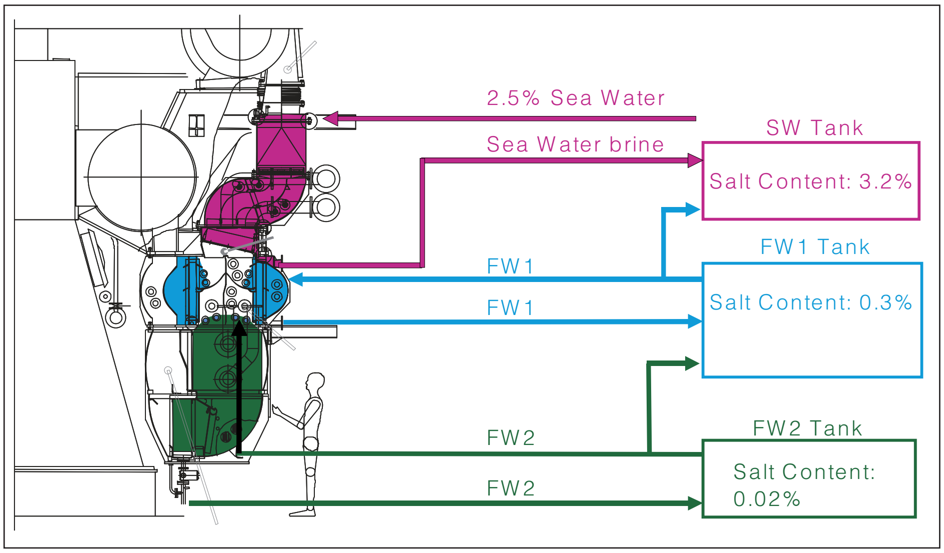


Fig. 11: Expected operation data at 100% load and ISO ambient conditions

Cooling system for the air cooler

The temperature of the scavenge air, and, thereby, the amount of water which is taken into the engine process, is controlled by the cooling water temperature of the air coolers. All of the evaporated sea water could, in principle, be condensed again in the air cooler. The engine performance would then correspond to operation in humid tropical regions. However, the presence of the highest possible absolute humidity in the scavenge air is wanted, as this reduces the formation of NO_x emissions. The intention is, therefore, to cool the scavenge air only sufficiently to generate the necessary freshwater for keeping the salt content in the freshwater stages down, and take as much water as possible into the engine process.

The cooling water inlet temperature for the air coolers in SAM mode can be raised by pumping water from the return line via a shunt pump, see Fig. 13. The condensation of water for freshwater stage 2 can, thereby, be adjusted to the required level.

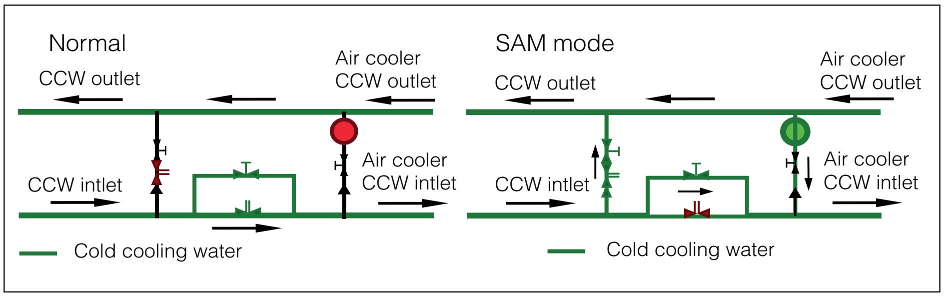


Fig. 13: Cooling of scavenge air

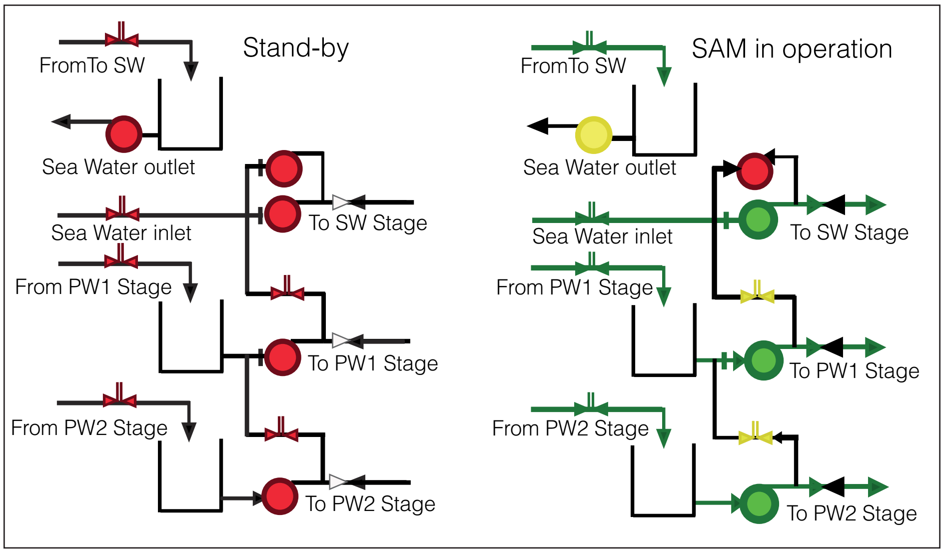


Fig. 13: SAM auxiliary system (operation of pumps and valves)

Control of the SAM system

The scavenge air moisturising system is controlled by a Programmable Logic Controller (PLC). The pumps and valves operate automatically depending on the status of the auxiliary system and the diesel engine. The auxiliary systems consist of 6 pumps and 13 valves in total, which are controlled based on approximately 50 digital and analogue inputs. The failsafe situation of all of the pumps and valves are normal operation of the engine without SAM.

The auxiliary systems of the SAM system, are started up automatically when the engine load is around 40-60% of SMCR. The freshwater stage 2 is started first, followed by the freshwater stage 1 and the sea water stage. As the last step, the scavenge air cooling will be changed over and the exhaust gas bypass valve is opened. The SAM system will, during stable engine operation conditions, be limited to control of the water level in the tanks by the yellow valves and pump. The SAM system is stopped in the opposite order of the start-up procedure.

Future of the SAM system

The principle of the SAM system is, in theory, a feasible way for reduction of the NO_x emissions from a diesel engine. Nevertheless, other aspects such as the impact on the cylinder condition by warm and humid scavenge air with salt need to be investigated thoroughly prior to any release in the market. The test on *M/V Mignon* will give valuable information on these aspects.

EGR system

The first EGR test made on an MAN Diesel two-stroke engine was the simplest possible set-up where the EGR system consisted 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 was completely avoided. The simplicity was an EGR without scrubber cleaning of the recirculated exhaust gas. Some kind of cleaning of this gas was previously proved to be vital for the operation in order not to foul and damage the air cooler and receiver components.

This first simple setup of the EGR system had two water injection stages, with a simple water separator unit after both. 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.

The conclusion from this test is a considerable reduction of NO_x, but it is doubtful whether the recirculated exhaust gas can be cleaned sufficiently before entering the air cooler and the scavenge air system.

Recently, MAN Diesel tested EGR with scrubber and water treatment. This resulted in a reduction of up to 70%, with a relative small penalty and, thereby, increase in fuel oil consumption.

The next step was to carry out a test on an engine in service.

Results from engine testing with EGR systems

Very promising operating conditions have been obtained during the tests.

The relative changes in the emission parameters were measured as a function of the recirculation amount. At increased recirculation amounts, the HC and PM emissions are reduced correspondingly 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.

A small 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.

The results from these measurements indicate that scrubbing reduces PM emissions 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.

The increase in CO emissions with increased recirculation amount indicates,

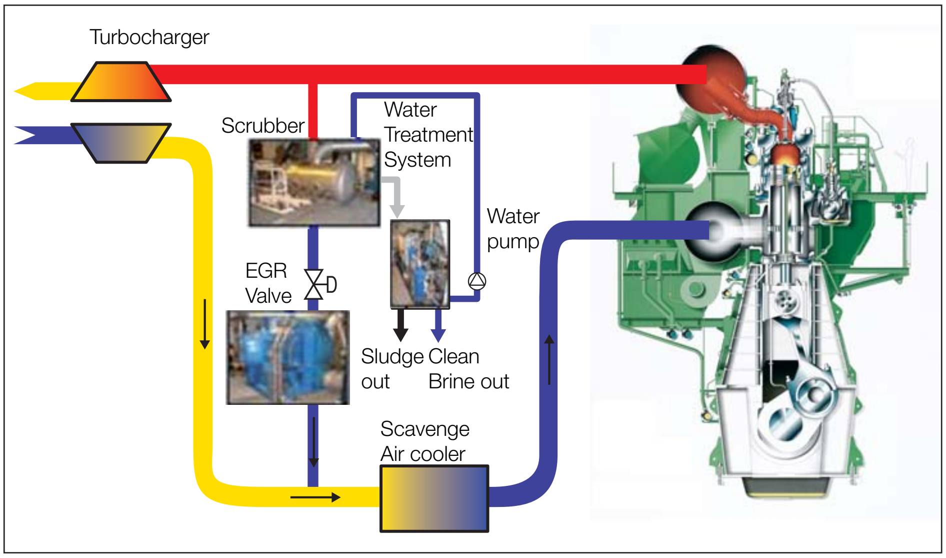


Fig. 14: CGR system

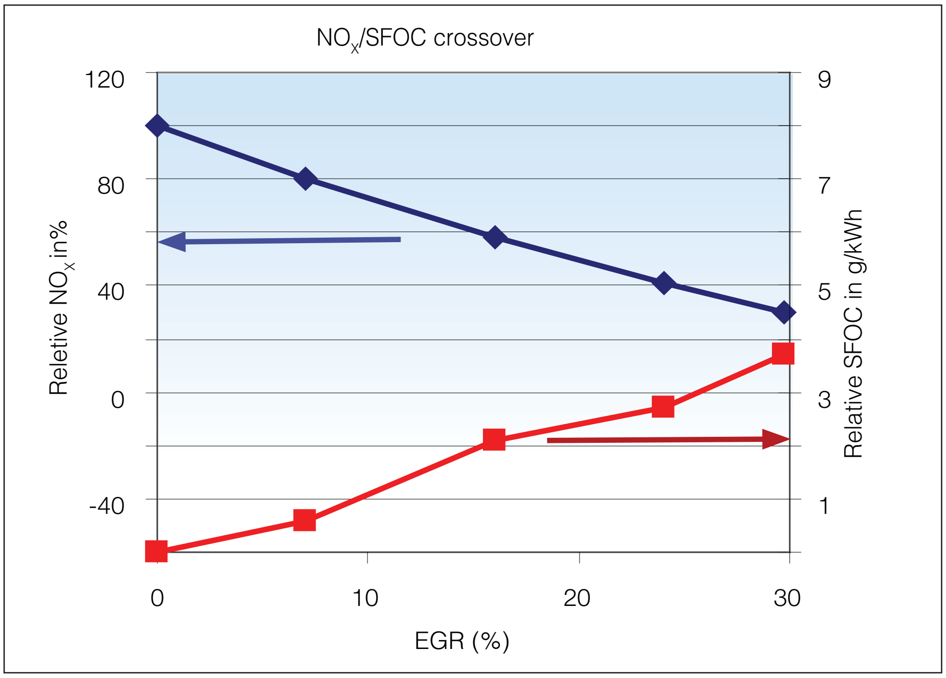


Fig. 15: NOx/SFOC relationship

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. Accordingly, MAN Diesel has measured the emission components at the inlet and outlet of the scrubber at different engine loads.

Accordingly, MAN Diesel started designing a completely new scrubber specially made for EGR up-stream systems. The MAN Diesel designed scrubber is shown in Fig. 17. Besides measuring engine performance, combustion chamber temperatures and emission data, extensive PM and SO_X measurements were performed before and after the exhaust gas scrubber during the EGR test. These measurements confirmed up to 90% PM trapping efficiency in combination with up to 70% SO_X removal, and absolutely no water carry over.

The performance of the EGR scrubber has proved so efficient that a test of evaluating the potential of this scrubber as after-treatment scrubber for two-stroke and four-stroke engines has been started.

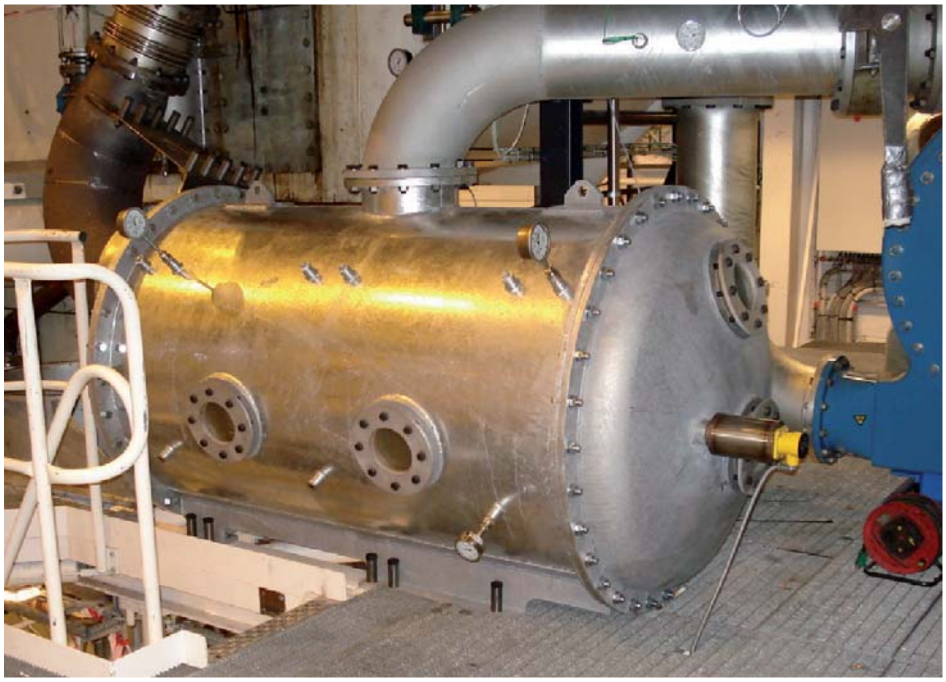


Fig. 16: The newly developed EGR scrubber applied to the test engine

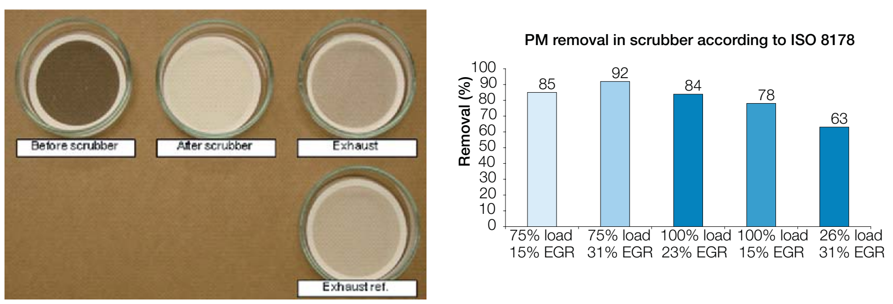


Fig.17: PM trapping efficiency

Extended combustion configuration and potential of the ME engine for emission control

With a tool like three dimensional CFD modelling, optic analyses of the combustion process, and operation on test engines reveal a huge potential for optimisation of the electronically controlled ME engine. During the last couple of years, investigations have been made and tested on the MAN Diesel research engine at constant engine speed, MEP (mean effective Pressure) and max. cylinder pressure at 75 and 100% loads, respectively.

The following issues were covered:

- injection timing
- exhaust valve open timing
- exhaust valve close timing
- compression volume configuration
- hydraulic pressure
- fuel valve flow area configuration
- injection profile including square profile and step profile.

The tests revealed that it is possible to obtain a variation in both SFOC and NO_x of approximately 10 g/kWh with unchanged MEP and p_{max}, giving very widespread optimisation possibilities. Even though the tendency for low NO_x values to give a high SFOC, the spread of values is so large that it is possible to obtain an improved NO_x performance with improved SFOC. All data obtained for the 75% load test are given in Fig. 18.

The injection pattern profiling is the main topic of our investigation of the ME control system. Fig. 19 shows four different heat release patterns related to four injection profiles. This illustrates that modelling the injection profile also means modelling the combustion pattern. All NO_x is generated during combustion and the modelling possibilities offered by the combustion pattern represent an excellent tool for controlling the NO_x formation and the cross-over between the NO_x for notion and SFOC.

The very positive result from these will of course result in a continued effort to investigate the further potential of the unique ME system, and transfer these findings to production engines as soon as verified. The step profiling is already systemised in the ME-B software and utilised as a setup for the delivery of the S40ME-B and S35ME-B engines. Further tests on S60ME-C, K98ME and L70ME-C type engines have been performed successfully.

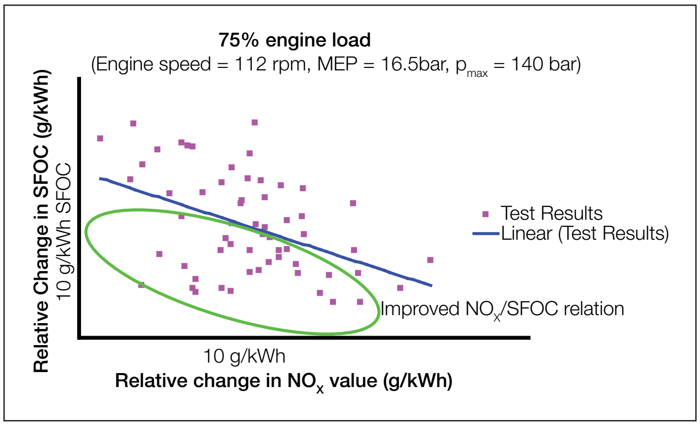


Fig. 18: Relative change in SFOC and NO_x at 75% load

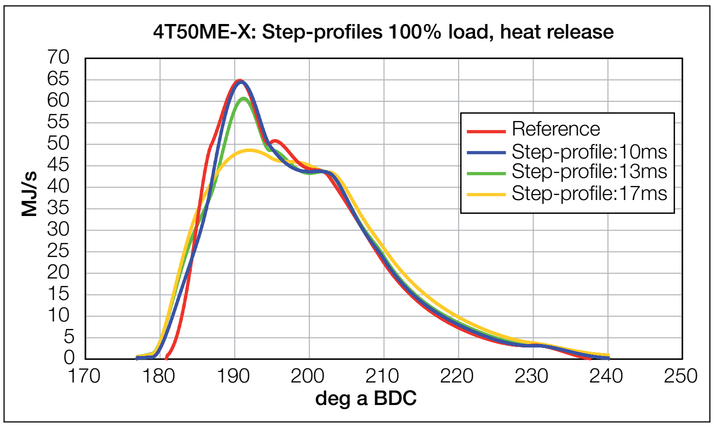


Fig. 19: Combustion pattern with different injection profiles

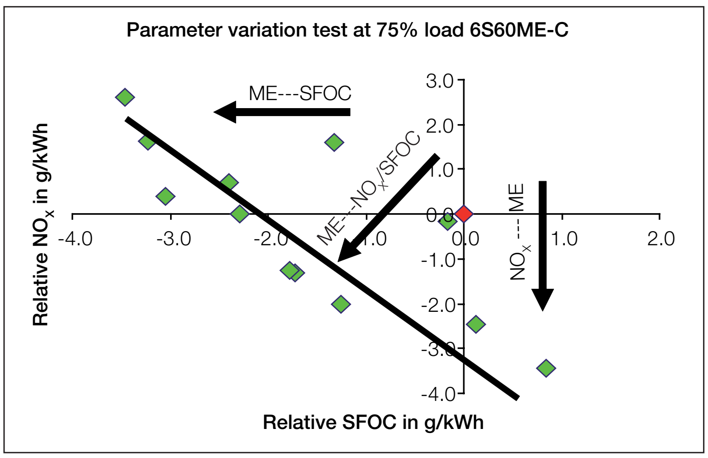


Fig. 20: Parameter test on 6S60ME-C

Fuels

Gas fuel operation

The MC/ME engine is a well-proven product in the industry, with more than 15,000 engines sold since 1982.

The GI (Gas Injection) solution was developed in parallel and was finished for testing at the beginning of the 1990s. In 1994, the first engine, the 12K80MC-GI-S, was started up on a power plant and has since operated as a peak load plant with more than 20,000 service hours on high-pressure gas.

At the same time, all major classification societies approved the GI concept for stationary and marine applications.

Recently, the engines have been introduced to the market for LNG vessels, and MAN Diesel has sold 90 sets of S70ME engines as prime movers for Qatar gas vessels. Technically, there is only little difference between the fuel and gas burning engines, but the GI engine provides an optimal fuel flexibility.

The thermodynamic condition in the combustion chamber is kept similar to that of the fuel burning when applying the 250-300 bar gas injection.

Power, exhaust gas amount and temperature values are the same as those of the HFO burning engines. The same performance conditions, choice of cylinder liner, cover, piston and cooling system are therefore unchanged from the HFO burning engine.

This gives confidence from the known performance of the proven diesel technology through many years.

Unlike other dual fuel solutions, the ME-GI has no limitation whatsoever in the use of natural gas quality, except that condensation in the system is not allowed. When operating the ME-GI engine, there is no derating and knocking due to the gas pressure and air flow, and general working principles of the two-stroke engine remain unchanged.

The gas system, including compressor, engine, piping, etc., has undergone three Hazid/Hazop investigations, explosion studies in the engine room and piping and volume tests to eliminate all possible risks on board.

Compared with HFO operation, gas gives a cleaner exhaust. Having very low or no sulphur, the SO_x sulphur oxides are negligible in the exhaust gas.

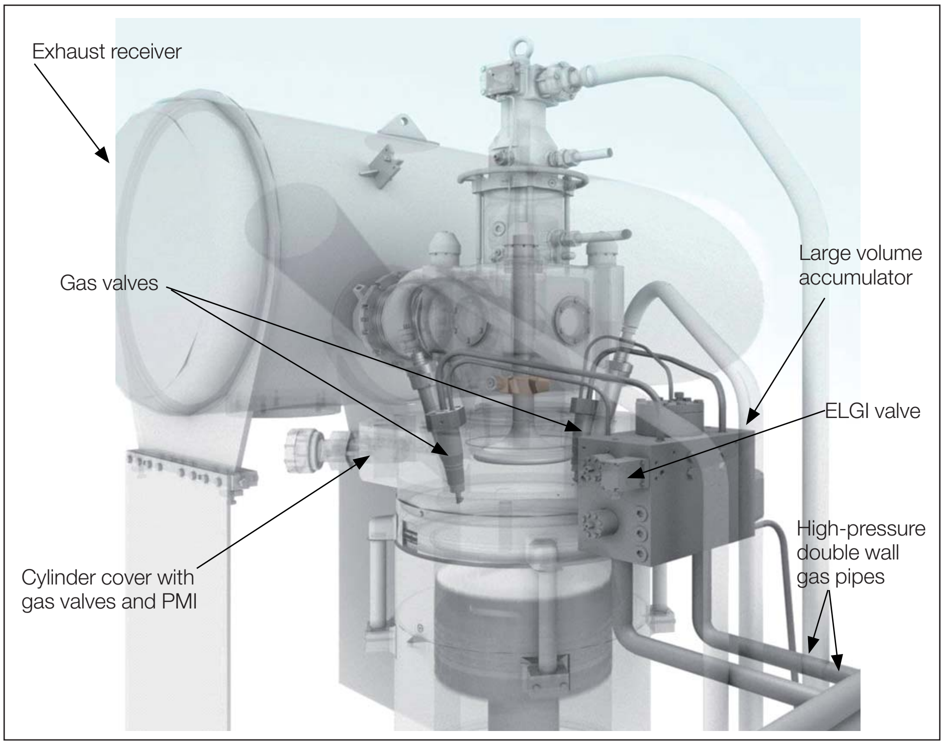


Fig.21: Components to be modified

Table III: Comparison of emissions from an HFO burning and a gas burning 70ME bore engine

Estimated emissions – 6S70ME-C		Estimated emissions – 6S70ME-GI	
Load 100%	g/kWh	Load 100%	g/kWh
CO_2	577	CO_2	446
O_2 (%)	1359	O_2 (%)	1340
CO	0.64	CO	0.79
NO_x	11.58	NO_x	10.12
HC	0.19	HC	0.39
SO_x	10.96	SO_x	0.88
PM (mg/m_3)	0.54	PM (mg/m_3)	0.34

The particulates will be reduced considerably as well as the emission of NO_x and CO_2.

The ME-GI technology is not limited to LNG carrier application. Investigations are in progress to see what is nessesary for other types of vessels. Container vessels and bulk carriers may also operate on LNG. The argument again is the relatively lower price seen for LNG, compared with HFO, combined with the improved emission values.

The gas can be evaporated to a compressor and be compressed to the 250 bar needed at the engine inlet, or by liquid pumps be pumped up to the 250 bar and be evaporated before going to the engine. Both solutions are available and known, and tested equipment is on the market.

Seawater scrubbers, abatement technologies

MAN Diesel cooperates with different companies developing seawater scrubbers for marine application. Whereas the power plant market has had products available for years now for different types of exhaust gas scrubbing, the limitations in space on board a ship and the different engine load patterns require a different way of thinking.

There is currently about 4-5 different companies in the market for marine application, and the first plant has been installed on a ship for testing. However, tests have so far only been made on smaller marine engines. Scrubbers for larger propulsion plants will require a different optimisation of the design, and various companies have realised that only when designing in smaller steps will it be possible to later cover the total range of engines onboard. The biggest challenge is the water amount, which seems to be quite large, and of course the fact that authorities specify limitations in the waste water being led back to sea.

MAN Diesel has tested a scrubber design that gave relatively high conversion figures and, thereby, a reduction in SO_x and PM. A full scale test with this scrubber solution to see the adaptation of this technology to real life is about to be launched.

As can be seen in Table IV, MAN Diesel is involved in a number of different actions to investigate the possibilities for scrubbing exhaust gas while at the same time ensuring that the techniques developed will give a safe and reliable operation of the main engine and, thus, the ship.

Table IV: Exhaust gas scrubbing projects

Objectives	Participants	Scrubber	Goals	Test results
Development and test of scrubber for after-treatment	Klaveness Vortex Clue MAN Diesel		PM trapping: >90% SO_x removal: >67%	PM trapping: 70% (with salts added) SO_x removal: 85% (with salts added) (no final test results)
Development and test of scrubber for after-treatment	Aalborg Industries Smit Gas MAN Diesel	No picture yet	PM trapping: >90% SO_x removal: >67%	No results yet
Development and test of scrubber for after-treatment and EGR	MAN Diesel		PM trapping: >90% SO_x removal: >67%	PM trapping (EGR): 92% SO_x removal (EGR): 70% (no final test results)

Also contact to: MES in Canada
LAB in France
Krystallon in UK

Low-sulphur fuel operation

Today, we have ECAs (emission control areas) based on EU and IMO regulations, in the Baltic Sea, the North Sea and the English Channel. And more such areas are expected to come. In the USA, the EPA (Environmental Protection Agency) is considering to designate Long Beach an ECA very soon.

The sulphur content has an impact on the sulphur acid emission to the air, sea and land, as well as a major impact on the particle level in the exhaust gas. Even though MAN B&W two-stroke engines are largely insensitive to the fuel quality, changing between fuels with different levels of viscosity is an important consideration to make.

The cylinder lube oil base number must be considered. Operating on normal BN 70 cylinder oil for too long when burning low-sulphur fuel will create a situation where the corrosion on the cylinder liners becomes too small and uncontrolled. The result is a creation of an excess of additive-generating deposits in the combustion chamber. Low-BN oil is available from the major oil companies, and recommendation on the use of low and high-BN oils are also available.

The fuel change-over process must follow the thermal expansion of both the fuel pump plunger and the barrel, and a procedure has been created to avoid causing damage to the fuel pumps. Furthermore, an automatic change-over unit will be available later this year.

In order to ensure the creation of a hydrodynamic oil film between the fuel pump plunger and barrel, a viscosity of 2 cSt is required at the engine inlet. This may be difficult to achieve for some DO and GOs, and some operators may have to introduce a cooler in the fuel oil system to ensure a satisfactory viscosity level.

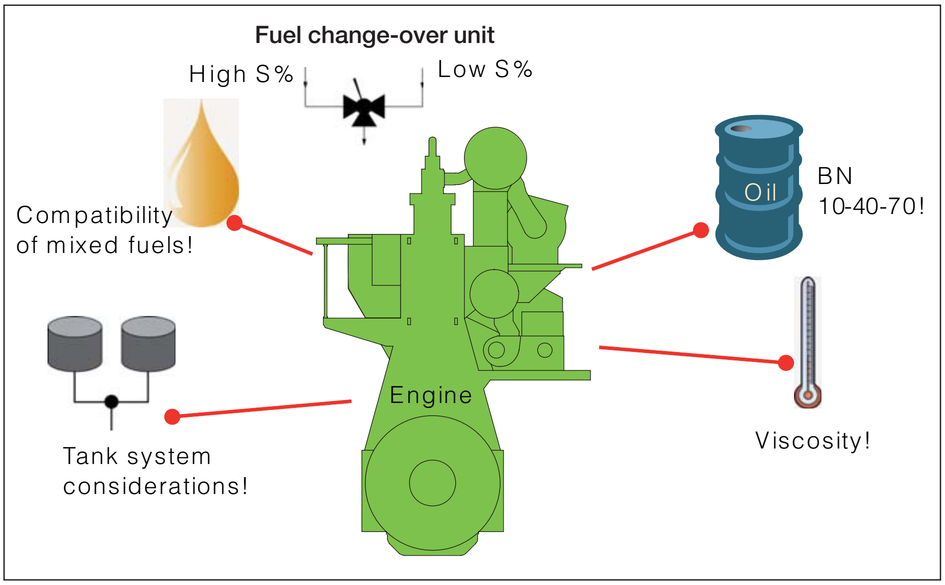


Fig.22: Low-sulphur fuel operations

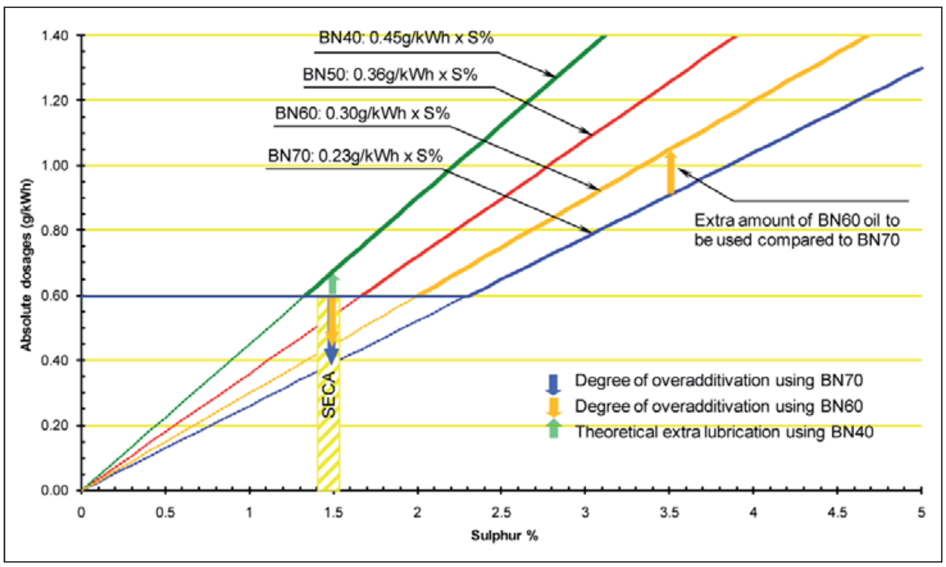


Fig.23: Low-sulphur fuel operations, choice of cylinder lube oil

The ignition quality of a fuel oil is not an issue for MAN B&W two-stroke engines. MAN Diesel has conducted a number of research tests showing that the MAN B&W two-stroke engine is insensitive to the poor ignition quality fuels on the market today.

A separate booklet called “Low-sulphur fuel operation” is available from MAN Diesel, Ref. [6].

Waste Heat Recovery System

For the large bore diesel engine, a combined cycle plant setup has so far been based on a standard design and, thereby, also standard performance of the diesel engine, leaving waste heat recovery (WHR) to boiler and steam turbine producers. Such a setup has of course contributed to improvement of the total efficiency of the combined plant, but not necessarily secured the best possible utilisation of fuel.

However, the overall task could be redefined. Instead of searching the optimal solution for the individual machines (engine, turbocharger, power turbine, boiler and steam turbine), a combined optimum for the entire process could be the target. The main success criterion is optimal efficiency (i.e. reduction of CO_2) of the system as a whole, however, with consideration to such side effects as emissions from the system.

Simple system calculations for two-stroke engine plants clearly indicate that a reduction of the scavenge air amount, and thereby increase of exhaust gas temperature level, which leads to reduced efficiency of the diesel engine itself, at the same time creates a remarkable potential for increased power output on both power turbines and steam turbines. The above-mentioned potential compensates the reduction of diesel engine efficiency with surplus.

Accordingly, the objectives are as follows:

- To encircle, by calculation and test, the level of reduced air flow through the engine, where thermodynamic parameters (performance), heat load on the combustion components, i.e. piston, exhaust valve, liner and cover, are not jeopardising the reliability of the diesel engine.
- To develop the principles and investigate, by calculations, different variants of combined systems starting in the above-mentioned results of the calculations and engine test.

  The variants of combined systems consist of the engine as a core element, boilers, power turbine (TCS) and steam turbine – all called Thermo Efficiency Systems (TES). Also variants of TES systems combined with Scavenge Air Moisturising (SAM) or Exhaust Gas Recirculation (EGR) systems are evaluated, as such systems will probably be applied on future engines due to expected new NO_x emission regulations, as well as for economical reasons of engine production.

Engine test
In order to confirm the potential, a reduced-air-flow test has been made on several engine types in the bore range S50ME-C to K98MC. The following will briefly report on the results obtained from the K98MC engine tests.

The simulation was made by introducing a cylinder bypass installed from the scavenge air receiver to the exhaust receiver and controlled by an adjustable valve and a scavenge receiver blow-off valve, see Fig. 24. Turbocharging efficiencies of ~60% to ~62% were simulated by observing the turbine inlet temperatures on the turbochargers and adjusting the bypass valve. The observed temperatures were then compared with calculated simulations.

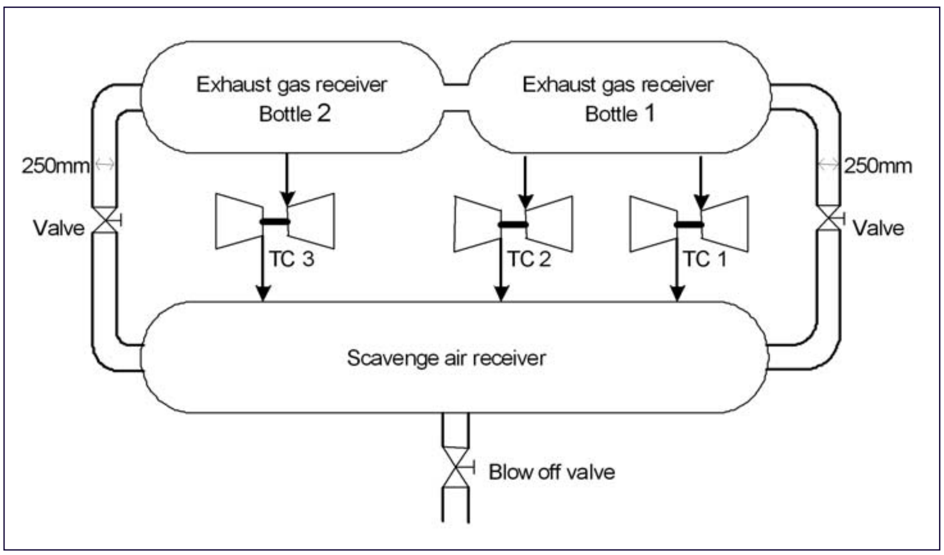


Fig. 24: Setup for TES engine simulation

SFOC and emissions
A comparison of measured SFOC and NO_x is given in Fig. 21.

The SFOC increases when the bypass is opened. This is fully as expected and pre-calculated, and is caused by the lower purity in the cylinder caused by the reduced air flow. However, the NO_x is slightly reduced, which is not completely in accordance with expectations and calculations, but of course represents a potential for reduction of SFOC by fuel system optimisations.

Combustion chamber temperatures
The combustion chamber temperatures for 100% engine load are shown in Fig. 22.

The result from the TES simulation test clearly confirms the pre-calculations.

The result also confirms that TES applications can be introduced in service without hesitation, when combined with the use of compound type slide fuel valves and pistons with Inconel cladding and cooling insert.

Traditional application available for commercial application
The TES engine application can be utilised in a traditional TES system with a significant benefit in overall efficiency of the vessel, as illustrated in Fig. 27.

The traditional TES application offers an improvement of the total plant efficiency of approx. 5%, corresponding to approx. 7,000 kW electric power production on 12K98MC/MC-C/ME/ME-C engines with approx. 73,000 kW shaft power.

Alternative application possibilities
The possibilities for TES engine application also allow for different options of other boiler TCS system configurations, as well as combining these TES applications with SAM and EGR applications.

TES applications
In all the investigated applications, the operating conditions have been equal to the standard TES application for the applications without SAM or EGR and corresponding to expected normal operating conditions for engines with SAM or EGR systems, see Fig.28.

System 1 is the traditional TES system and is used as reference in the following.

In System 2, the boiler has been divided into a low-temperature section after the turbocharger, and a high-temperature section before the turbocharger and power turbine. The benefit of this application is the possibility to increase the steam superheating temperature from approx. 280ºC to approx. 440ºC, increasing the steam turbine efficiency significantly. The disadvantage is a reduced TCS power turbine output due to reduced inlet temperature and reduced gas flow rate.

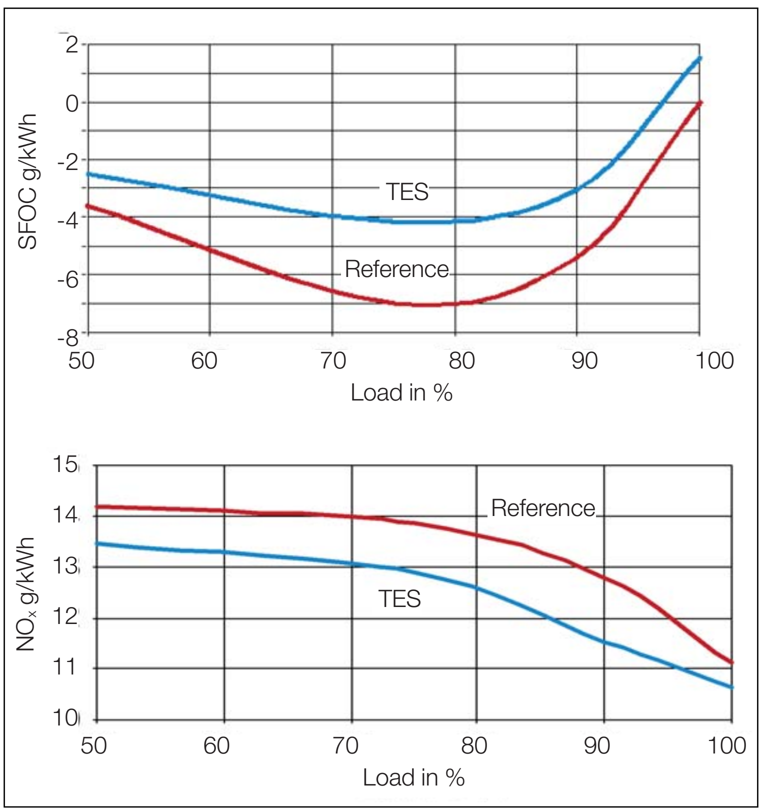


Fig. 21: SFOC and NO_x measured

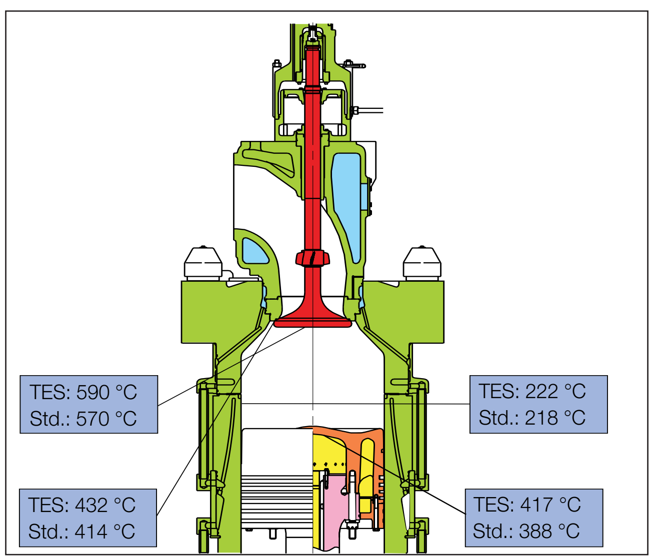


Fig. 22: Combustion chamber temperature reference and TES mode

Combining System 2 with SAM, results in System 3, also shown in Fig. 28. The SAM system in 3 increases the potential bypass flow to the power turbine and, accordingly, increases the power turbine power. The advantages and disadvantages of having both a low-temperature and a high-temperature boiler are the same as for System 1.

Systems 4 and 5 correspond to Systems 2 and 3, with the only difference that the high-temperature boiler is moved from the main exhaust gas stream to the bypass exhaust gas stream. By moving the high-temperature boiler from main stream to bypass stream, the bypass mass flow and the heat balance of the turbocharger are unaffected by the high-temperature boiler. The advantage of this system is that the power turbine is reduced only due to lower inlet temperatures. The disadvantage is that the possible power extraction in the high temperature boiler is very limited.

Fig. 28 illustrates five alternative system applications, which have been investigated by calculations only. The calculations were performed in cooperation with Aalborg Industries for the boiler calculations and with Peter Brotherhood Ltd. for the steam turbine calculations. In this last set up in Fig. 28 (System 5), the high and low temperature boilers are combined with an EGR system. The advantages of this system are that the power turbine is reduced only due to lower inlet temperatures and that the gas flows through the high temperature boiler are relatively high, because the EGR flow also goes through the boiler.

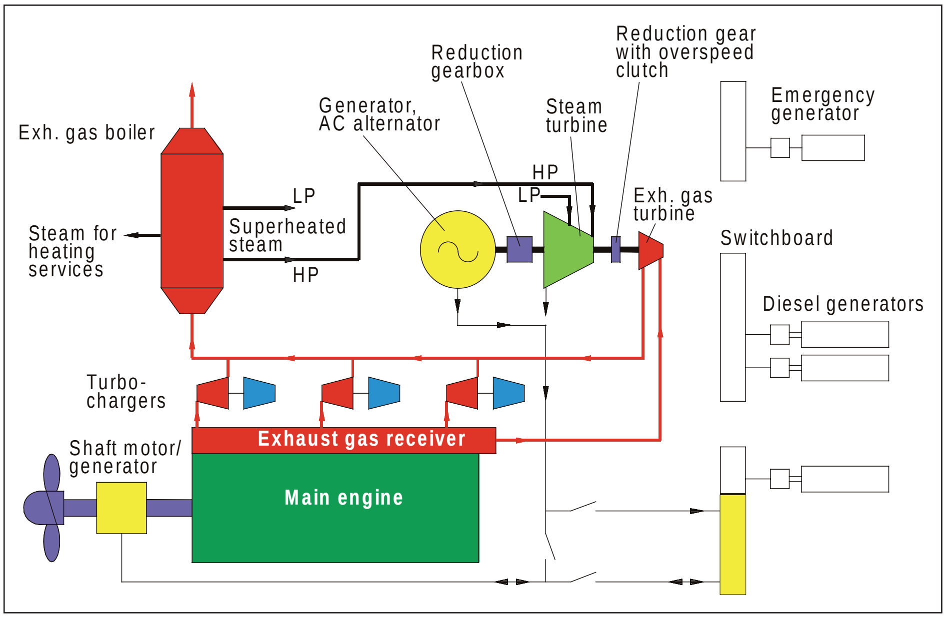


Fig. 27: Traditional TES application

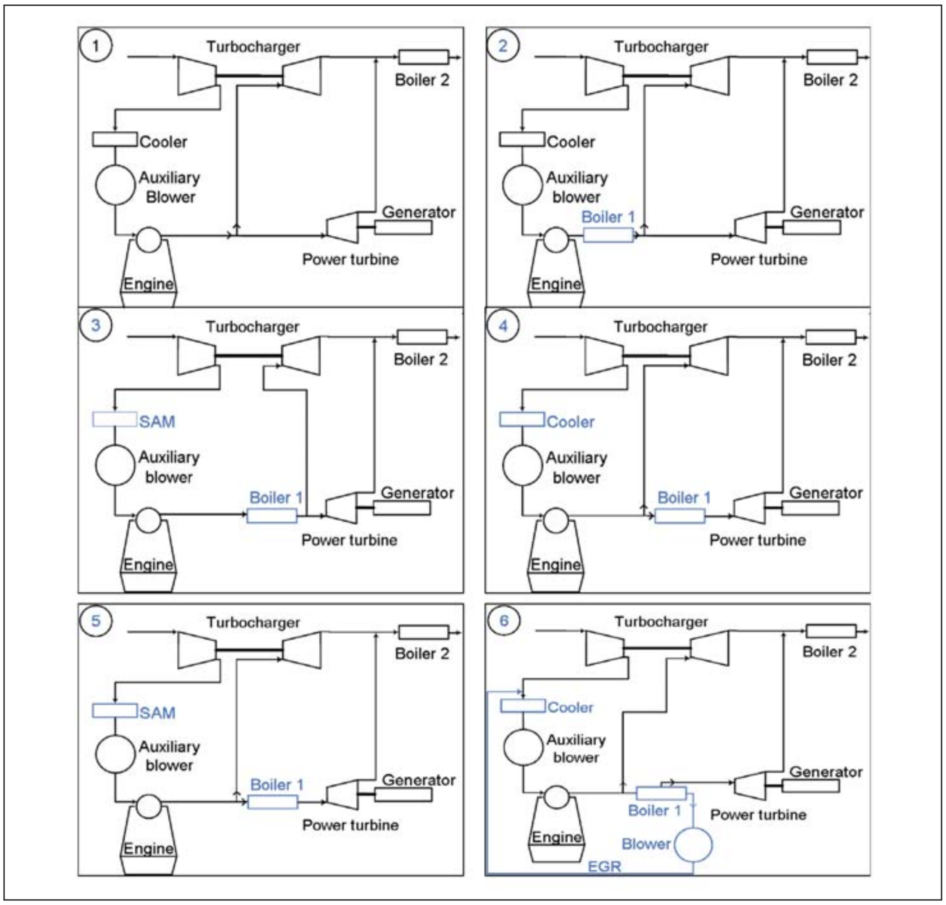


Fig. 28: One standard and 5 alternative TES applications

Calculation results

In order to calculate the possible impact of the different set-ups, Aalborg Industries has made the calculation model shown in Fig. 29, giving extended possibilities for building all kinds of systems.

Summation of results

A comparison of the results of the six cases reveals the optimum case.

Table V clearly shows that case 5 gives the best result, both in terms of electrical power output and efficiency. It is no coincidence that the case with the highest power turbine output has the highest electrical efficiency.

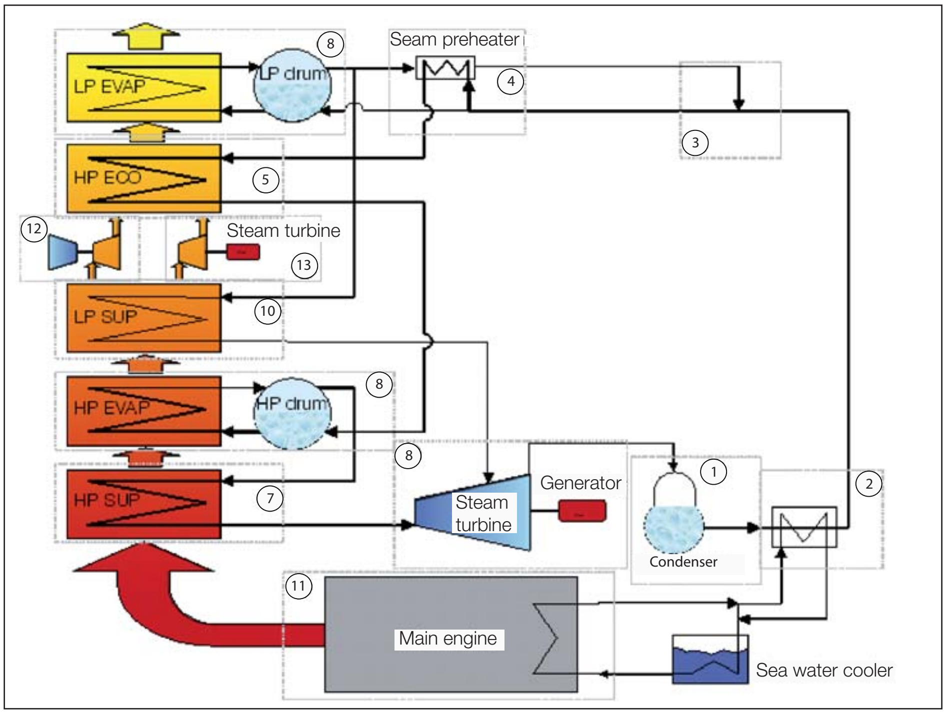


Fig. 29: Flexible calculation model from Aalborg industries

Table V: Calculation results

	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
LP pressure [bara]	7	7	7	7	7	7
LP superheat temperature [°C]	270	440	446	281	266	277
HP pressure [bara]	-	-	-	19.5	10	10
HP superheat temperature [°C]	-	.	.	440	446	443
Heat extraction in Boiler 1 [kW]	0	4135	4840	2902	4781	9504
Heat extraction in Boiler 2 [kW]	20900	16460	18880	17840	19420	16420
Power turbine [kW]	3017	2080	2262	2436	4418	2379
Steam turbine [kW]	3798	5590	6451	6350	7922	7113
Total electrical power [kW]	6815	7670	8713	8786	12340	9492
Power rel. to main engine [%]	10	12.2	12.7	12.8	18.0	13.9
Resulting heat rate						

Existing Engines Converted to Tier I

The IMO Marpol Annex VI has informed that the NO_x control of existing engines is to be regulated. The regulation will concern engines of 5,000 kW, or larger, installed on ships built from 1 January 1990 to 31 December 1999. This requires a retrofit kit to be available for those engines, or that an approved method of changing and showing compliance with IMO Tier I is available.

The kit for retrofitting the MC/MC-C engines from that period is available from MAN Diesel as the assistance to make the necessary procedures to be in compliance. The kit basically contains injection valves designed for IMO Tier I compliance. For more information, please contact PrimeServ Denmark.

Two-stroke MAN B&W Emission Projects in Progress

With regard to SO_x and PM regulation, this is decided to be controlled by limitations in the sulphur content of the fuel used. An alternative measure is the use of scrubbers.

- **Water emulsion**
  On an 11K90MC engine APL Singapore, test engine.

- **Low-sulphur fuel operation**
  Laboratory test, fuel pump test, and test in service on a ship. Initiated by CARB, APL, APM, SeaSpan and MAN Diesel.

- **SAM (scavenge air moisturising)**
  Full scale test on a 6S60MC engine on a Wallenius Wilhelmsen car carrier. The test is in progress.

- **EGR (exhaust gas recirculation)**
  Test on the MAN Diesel 4T50ME-X research engine in Copenhagen has already been completed, and a 70% NO_x reduction was achieved. A full scale test at sea is scheduled in 2009 together with a European shipowner.

- **Scrubber and after-treatment**
  to remove SO_x and PM has been successfully tested at Holeby on an Israeli scrubber design in cooperation with a Norwegian shipowner. A full-scale test is scheduled in 2008 in co-operation with the same shipowner.

- **Fuel switch**
  A new change-over system from DO/DG to HFO, and vice-versa, has been developed to protect the engine. Will be tested at sea in 2008.

Conclusion

Tier II and Tier III of IMO Annex VI are currently being discussed in order to specify the acceptable levels of exhaust gas emissions in the years to come.

The MC and ME type MAN B&W engines will be able to meet the Tier II NO_x limits by internal engine methods.

The expected Tier III 80% NO_x reduction requirement can currently only be met by the use of external engine methods such as SCR.

However, by development and research, MAN Diesel has been able to achieve a NO_x reduction of 70% by means of internal methods such as SAM and EGR. In the coming years, these systems will be matured to the market.

According to IMO, SO_x and PM will be reduced by fuel sulphur level limits. Alternatively, an abatement system can be installed, e.g. a fuel oil scrubber solution. MAN Diesel is also investigating this option to ensure a safe, reliable and environmentally friendly operation of MAN B&W propelled vessels.

It is difficult to further reduce the CO_2 emission level created by the two-stroke process. However, by utilising the waste heat, an improvement of the total energy utilised from fuel burned is achieved. Various system configurations offer up to 60% efficiency.

High fuel prices and emission concerns have increased the focus on utilising natural gas as fuel oil. Not only in the LNG market, but also for other types of commercial vessels traditionally operating on HFO. The MAN Diesel engine programme covers this growing market with the low speed MAN B&W gas operating ME-GI type engine and the medium speed L51/60DF type engine.

References

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[3] "NO_x control in practice and demands made on owners and engine builders", MAN B&W Diesel paper for meeting at the Maritime Museum in Bergen, March 2000

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

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

[6] "Low-sulphur fuel operation" paper published by MAN Diesel A/S, Copenhagen

List of Abbreviations

SAM Scavenge Air Moisturising

IMO International Maritime organisation

EPA Enviremmental Protection Agency
MEPC

SCR Selective Catalytic Reduction

SECA Sulphur Emission control Area

HFO Heavy Fuel Oil

OO Diesel Oil