Tier III Two-Stroke Technology
# Contents

Introduction ................................................................................................. 5  
Tier III Technologies ................................................................................ 5  
SCR Application for Tier III ................................................................. 6  
   Fuels for Tier III engines ................................................................. 6  
   Selective catalytic reduction ............................................................. 6  
   SCR system for MAN B&W engines ................................................ 7  
   SCR control system ........................................................................... 10  
Results and discussion ......................................................................... 11  
SCR and HFO operation ............................................................................. 15  
SCR service experience ............................................................................. 15  
   Future development aspects ............................................................. 15  
Conclusion ................................................................................................. 17  
EGR Application for Tier III ................................................................. 18  
   EGR investigation on 4T50ME-X ......................................................... 18  
   EGR Tier III confirmation test ........................................................... 19  
   EGR scrubber performance ............................................................... 19  
   EGR service test .................................................................................. 21  
   Preparation of service test on newbuilding with 6S80ME-C9.2 .......... 23  
   Water treatment system (WTS) ........................................................... 25  
   EGR high-speed blower ...................................................................... 27  
Conclusion ................................................................................................. 29
Tier III Two-Stroke Technology

Introduction
This MAN Diesel & Turbo two-stroke Tier III paper outlines the status and future development efforts in connection with Tier III technologies, and covers some of our efforts to develop measuring and calculation tools, securing better knowledge of engine processes like combustion, emission formation and scavenging of the engine.

Furthermore, details on the SCR development, not only for the catalyst application, but also on the requirements to the engine control system in connection with the SCR application are given. Also, the status on service tests on the world’s first Tier III two-stroke engine will be outlined.

SCR application is challenging due to the requirement for installation on the high pressure side of the turbocharger, and it is space requiring due to the size of the SCR and urea mixing unit. It is accordingly relevant to evaluate if SCR applications can be further integrated in the engine design for compacting and securing easy application.

The EGR development project will also be described in detail, not only test results from research engines will be covered, but service results from prototype tests of the EGR system on the Alexander Maersk will be outlined, together with an update on the design for the latest and fully integrated EGR design on a 6S80ME-C9.2 engine, which will form the basis for the complete Tier III engine programme with EGR.

The Tier III EGR application will also open for the possibility of utilising EGR as Tier II reduction technology and optimisation of part load operation of the engine outside the EGR areas. Operation modes for both ECA and non-ECA areas will be outlined.

As both EGR and after-treatment scrubbers for SO₂ removal require WTS (Water Treatment Systems), we have, in cooperation with external partners, ensured that a significant development effort is in progress also in this area.

Finally, our latest achievements within advanced measuring and calculation methods, for better understanding of combustion, and emission formation and scavenging of two-stroke engines will be discussed in this paper.

Tier III Technologies
IMO Tier III is mandatory for engines installed on vessels constructed after 1 January 2016 when operating inside an Emission Control Area (ECA). For an engine designer, it consists of three main requirements:
- An 80% NOₓ-cycle value reduction, compared to the Tier I level
- A 150% mode cap on each load point in the cycle (the “not to exceed limit”)
- Tier III applies when operating the engine in a NOₓ emission control area.

Each of the three requirements is important when developing the technology necessary for Tier III engines. The 80% load cycle NOₓ reduction requirement means that internal engine optimisation is not sufficient – in other words: new technology is necessary.

The mode cap on the individual mode points of the load cycle means that the applied solutions have to suit a wide en-
The main focus in the following will be on the SCR path for compliance with Tier III NOx regulation chosen by MAN Diesel & Turbo for low speed two-stroke marine diesel engines.

**Fuels for Tier III engines**

Cost aspects are critical for the success of a technology. This is the case for both first cost and for operating costs. Many parameters affect the cost evaluation, as ships operate with different ownership models, different trade patterns and different engine operation profiles. Added to those differences are uncertainties regarding prices and availability of fuel and other consumables needed for the Tier III systems. Large marine diesel engines operate on a wide range of fuel qualities, ranging from low-viscosity ultra-low-sulphur distillates to very high-viscosity residual fuels.

All MAN B&W Tier III engines will be capable of running on low-sulphur fuels and, at the same time, options will be available for complying with the fuel sulphur limits by other means, thus enabling heavy fuel oil (HFO) operation.

**Selective catalytic reduction**

A way of meeting the IMO Tier III NOx limits is to install a selective catalytic reduction (SCR) reactor. In the reactor, NOx is reduced catalytically by ammonia (as urea) to nitrogen and water, see Fig. 1.

SCR reactors have been used in power plant applications since the late seventies, and MAN Diesel & Turbo (MDT) was involved in one of the first marine applications in 1989 on large two-stroke diesel engines. However, whereas the technology is mature for robust power plant applications, the technology still needs to be matured for daily marine operation. Therefore, MDT is involved in a targeted development of this technology together with Hitachi Zosen Corporation. Hitachi Zosen builds MAN B&W engines and has, among others, a division that develops and delivers SCR catalysts.
The SCR collaboration was initiated in 2008, and in the following period extensive development and tests have been conducted on a 1S40MC and a 6S46MC-C engine fitted with SCR systems.

MDT’s focus has been on the development of a dedicated SCR engine that ensures reliable SCR operation when HFO is employed. Hitachi Zosen’s focus has been centered on the development of SCR systems for large two-stroke diesel engines.

**SCR system for MAN B&W engines**

**Preconditions for SCR operation**

Due to the high-energy efficiency of two-stroke diesel engines, the exhaust gas temperature after the turbocharger is low: typically in the range from 230-260°C after the turbocharger dependent on load and ambient conditions. These low temperatures are problematic for the SCR when HFO is employed. Thus, in order to achieve the highest possible fuel flexibility, it has been a priority to ensure that the engine produces an exhaust gas with the right temperature for the SCR system.

The SCR inlet gas temperature should ideally be around 330-350°C when the engine is operated on HFO.

**System configuration**

At present, the too low exhaust gas temperature after the turbine has called for a solution where the SCR is placed on the high pressure side of the turbine. Depending on the engine load, this makes it possible to obtain exhaust gas temperatures that are between approximately 50°C and 175°C higher than after the turbine. Compare Table 1 and Fig. 2.

This means that the SCR system works according to the following: When NO\_x reduction is needed, the exhaust gas is guided to the SCR according to the flow direction illustrated in Fig. 2. When no SCR operation is needed, the exhaust gas is passed directly to the turbine in the turbocharger (T/C) and the SCR is sealed by two valves.

**Table 1**

<table>
<thead>
<tr>
<th>T\text{amb}=10\degree\text{C}</th>
<th>25% load</th>
<th>50% load</th>
<th>75% load</th>
<th>100% load</th>
</tr>
</thead>
<tbody>
<tr>
<td>T\text{in turb.}\ [\degree\text{C}]</td>
<td>299</td>
<td>308</td>
<td>337</td>
<td>395</td>
</tr>
<tr>
<td>T\text{out turb.}\ [\degree\text{C}]</td>
<td>245</td>
<td>217</td>
<td>207</td>
<td>221</td>
</tr>
<tr>
<td>T\text{gain}\ [\degree\text{C}]</td>
<td>54</td>
<td>92</td>
<td>130</td>
<td>174</td>
</tr>
</tbody>
</table>

Table 1 reveals that even though the reactor is placed before the turbine, the exhaust gas temperature is still too low at loads below approximately 50%. Therefore, it has been necessary to develop a “low load method”, which can be used to increase the exhaust gas temperature.

**Fig. 2: Arrangement of a high-pressure SCR solution on a 6S46MC-C engine**
temperatures. This is the cylinder & SCR bypass shown in Fig. 3.

The cylinder bypass valve (CBV) increases the exhaust gas temperature by reducing the mass of air through the cylinders at a fixed amount of fuel combustion. This means that higher exhaust gas temperatures for the SCR are obtained. Calculations have shown that this method is suitable, because the mass flow through the T/C remains almost unchanged. This means that the scavenge air pressure is maintained, and thus that the combustion is nearly unaffected.

From a combustion chamber temperature point of view, the low-load method constitutes a challenge, because the mass of cooling air through the cylinders is decreased. This is an effect that needs to be investigated during test bed operation.

**Engine control system**

In addition to the development of the low-load method, a new engine control system (ECS) has been developed. This is needed, because the SCR has a significant heat capacity. Due to the fact that the SCR is fitted before the turbocharger, this constitutes a challenge for the energy balance between the engine and the turbocharger. Thus, it is necessary to bypass some of the exhaust gas directly to the turbocharger during engine start-up and acceleration in order to ensure sufficient energy input.

**Items to be controlled by the ECS**

<table>
<thead>
<tr>
<th>Item</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>V1</td>
<td>Maintains acceptable turbocharger performance</td>
</tr>
<tr>
<td>V2</td>
<td>Limits effects on engine performance</td>
</tr>
<tr>
<td>V3</td>
<td>Seals reactor together with V2</td>
</tr>
<tr>
<td>CBV</td>
<td>Increases low-load exhaust gas temperature</td>
</tr>
<tr>
<td>A/B</td>
<td>Stabilises T/C</td>
</tr>
</tbody>
</table>

Table 2

Fig. 3: Low-load method to increase exhaust gas temperatures
to the turbine. For the same reason, it may be necessary to bypass the turbine during de-acceleration of the engine, as the energy level of the exhaust gas from the SCR is too high. Lastly, the low-load method needs to be controlled to ensure the right temperature at the SCR inlet. As a result, a dedicated ECS has been developed for the SCR engine. The outline of the ECS is illustrated in Fig. 4.

The success criteria for the ECS are:

- To ensure acceptable engine performance
- To ensure quick heating of the SCR system
- To ensure a minimum exhaust gas temperature $T_{min}$.

Fig. 4 shows three bypass valves which control the distribution between the exhaust gas that goes to the SCR system and the exhaust gas that goes directly to the turbine. These are called: V1, V2 and V3. Furthermore, the CBV are displayed on the figure. The ECS also controls the auxiliary blowers (A/B), which have been fitted with larger electrical motors to assist during heating of the SCR and engine accelerations. The A/Bs are able to operate in the entire load range of the engine. The functions of the individual valves are summarised in Table 2.

The four valves and the A/Bs are an integrated part of the ECS, and they are controlled on the basis of three continuous temperature measurements of the exhaust gas. These are also found in Fig. 4: T1, T2 and T4. T1 is the exhaust gas temperature in the exhaust gas receiver, T2 is the exhaust gas temperature at the inlet to the turbine, and T4 is the exhaust gas temperature at the outlet of the SCR reactor.

The difference between T1 and T2, denoted $dT$, is an expression for how much the energy balance between the engine and T/C is influenced because energy is either lost or gained by heating/cooling of the SCR system. In the present system, a $dT$ of 50°C has been found to ensure acceptable engine performance.

V1 and V2 open and close according to the limit given by $dT$, i.e. 50°C. V3 is an on/off valve. Urea is injected when V1
is fully closed, and the T1 is above the critical temperature for urea injection.

Based on these three temperature measurements, the ECS is able to ensure that the engine performance is maintained during deceleration/acceleration and heating/cooling of the SCR system. Furthermore, the ECS ensures that the exhaust gas temperature is kept above a certain $T_{\text{min}}$ by adjusting the position of the CBV.

The four bypass valves are all of the same butterfly type and are designed by MDT, see Fig. 5. V1, V2 and V3 are gas tight and are sealed by scavenge air. This is to avoid any condensation of exhaust gas in the SCR elements during non-SCR operation.

During engine tests in January and February 2011, the ECS was commissioned, and a print of the main operating panel (MOP) is shown in Fig. 6. The ECS is able to handle all aspects related to the handling of the engine: heating of SCR, deceleration and acceleration.

**SCR control system**

The SCR unit, including the urea dosing system, also needs to be controlled in order to ensure the right amount of urea injection at different loads and NO$_x$ emission levels. Furthermore, the urea injection system needs a flushing sequence during SCR close-down, and soot blowing of the catalyst elements. Hitachi Zosen has developed and delivered this control system.

The dosing of urea is based on online NO$_x$ measurements before and after the SCR reactor with a ZrO$_2$ based sensor. The measured value is compared with
an estimated NO\textsubscript{x} value based on test bed measurement (NO\textsubscript{x} map as a function of engine load). This is to ensure that no under/over dosing of urea takes place in case of a sensor error.

**Results and discussion**
A full scale SCR system has been installed on a 6S46MC-C engine at Hitachi Zosen’s workshop in the Ariake Prefecture of Japan, see Fig. 7. Details of the engine and SCR system are shown in Table 3.

![Image: Full-scale SCR system](image)

**Table 3**

| Engine and SCR used for full scale SCR tests |
|-------------------------------|-----------|
| Cylinders                     | 6         |
| Bore                          | 460 mm    |
| Stroke                        | 1,932 mm  |
| Output                        | 6,780 kW @ 111 rpm |
| MEP                           | 19 bar    |
| Location of SCR system        | Before turbine |
| Reducing agent                | Urea solution (32.5 wt%) |
| Total mass of SCR line        | 15,000 kg |
| Mass of SCR catalyst          | 1,900 kg  |
| Type of catalyst              | Corrugated honeycomb (TiO2/V) |
| Manufacturer of catalyst      | Hitachi Zosen Corporation |
| Manufacturer of SCR equipment | Hitachi Zosen Corporation |

![Diagram: SCR system components](image)
A huge number of tests with various goals were conducted on this system in the period from January to April 2011. The objectives were the following:
- To investigate low-load method
- To commission ECS
- To verify Tier III compliance
- To gain experience on SCR operation in combination with HFO.

Low-load method at 25% engine load

The low-load method has been tested at engine loads ranging from approximately 10% to 50%. Three issues were the main objectives:
- Possible temperature increase of exhaust gas entering the SCR
- Penalty on combustion chamber components temperatures
- Penalty on SFOC.

In the following, the results obtained at the lowest IMO load point (25% engine load) is discussed – this is where the lowest T1 temperature is obtained. The amount of scavange air through the bypass was adjusted and the SFOC and combustion chamber temperature (CCT) was measured, among other things. The CCT measurements showed that the average temperature of the exhaust gas spindle (X/V spindle) was the most influenced component, for which reason the other combustion chamber components (cylinder liner and piston) are omitted in the discussion.

During the reference test, the exhaust gas temperature, T1, was measured to 258°C. This means that T1 should be increased by at least 72°C to obtain a temperature above the mentioned 330°C minimum SCR inlet temperature.

Plot 1: Influence of increased T1 on X/V spindle (full line) and SFOC (dashed line). T1 is increased by opening CBV.

Plot 2: Loading from 20% to 100% of the engine to maintain SCR operation.
With fully open CBV, T1 can be increased by 165°C. This means that the desired temperature increase of 72°C is obtainable. From Plot 1, it is revealed that this temperature increase causes an increased heat load of approx. 25°C on exhaust valve and an SFOC penalty of approx. 2-3 g/kWh.

Based on the investigations of the low-load method, it has been concluded that for the present system, the CBV will be employed. However, in future applications, increased scavenge air temperature in combination with CBV may be needed to ensure SCR operation at even lower engine loads.

**Engine control strategy**

The ECS was also tested on the 6S46MC-C engine on the test bed. A typical heating of the SCR system during engine loading from 20% to 100% is shown in Plots 2 and 3. At time equals to 0, the engine is operated at 20% engine load and the SCR system is in steady condition. This is followed by acceleration to 100% engine load. Plot 2 shows the development of T1 and T4, and Plot 3 shows the valve positions during the same period.

It can be seen that CBV is able to maintain T1 at the desired \( T_{\text{min}} \) of 310°C by slowly closing as the engine load increases.
After a certain period, the CBV is closed (Plot 3) and T1 increases with the engine load. It is also important to observe that this loading ensures that V1 remains closed and thus ensures full NOx reduction at all times. In cases where V1 is opened due to too high dT, the urea injection is set at a very low flow to avoid NH3-slip.

Another cause of heating of the SCR system has been posted in Plot 4. In this case, the engine is operated at 100% engine load, thus T1 is well above Tmin of 330°C.

The SCR system, which is at ambient temperature, is engaged at time equals 0: V3 opens, V2 opens according to a dT of 50°C followed by closure of V1 also according to dT equals 50°C. V2 is opened during the first two thirds of the time before urea injection starts, and V1 is closed during the next period. Subsequently, the SCR system is ready for urea injection.

The plots illustrate that the ECS is able to handle the operation of the SCR system. It is also concluded that with normal loading and unloading speeds of the engine, it is possible to keep the SCR system engaged at all times. In addition, the tests show that the SCR system needs a certain time for heating before it is ready for NOx reduction.

**IMO Tier III operation**

It was also verified that the engine and SCR system was able to meet the IMO Tier III NOx limits, and the results are displayed in Table 4. The results were witnessed by ClassNK (Nippon Kaiji Kyokai) in April 2011. The table reveals that the SCR system ensures a NOx cycle value of 2.8 g/kWh, which is well below the IMO Tier III limit of 3.4 g/kWh. Based on these measurements, it was concluded that the world’s first Tier III compliant two-stroke engine has been demonstrated. The next important step is the further testing of the system, which is presently installed on a general cargo carrier. The ship was built at the Nakai shipyard and entered active service in late 2011. The owner of the vessel is the Japanese BOT Lease Co. Ltd., and the vessel is operated by Nissho Shipping Co. Ltd.

<table>
<thead>
<tr>
<th>NOx emissions at the four IMO engine load points</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tier III</td>
</tr>
<tr>
<td>g/kWh</td>
</tr>
</tbody>
</table>

Table 4
SCR and HFO operation

It is well known that the combination of sulphur containing fuels and SCR is challenging. This is because of the transformation of SO$_2$ to SO$_3$ inside the SCR. This allows formation of ABS and white plumes. In addition, it is also known that the inherent content of vanadium in HFO makes the SO$_2$ oxidation more pronounced over time. It is necessary to demonstrate that the present SCR system has been designed in a way that suppresses these undesired side reactions. This is a part of the service test which was initiated in the last part of 2011.

SCR service experience

Having concluded that it is possible to meet the IMO Tier III limit with the system presented in Table 4 and Fig. 7, this system was moved from the test bed to the general cargo carrier Santa Vista, see Fig. 8. Details of the ship are found in Table 5.

The system was commissioned in October 2011 and Tier III operation was confirmed. The Licence Days 2012 paper No. 9 from Hitachi covers installation aspects and the service experience gained up to now.

Future development aspects

Obtaining a uniform ammonia concentration in an exhaust gas poses a multifaceted problem. Common practice is to inject urea as a liquid into the exhaust stream via a spray nozzle. The urea evaporates and undergoes a chemical decomposition to form ammonia. This is troublesome as the process is fairly slow compared to flow time scales, as droplets impinging on walls may deposit and form solid structures, which may eventually clog the system. While this has to be avoided, the SCR unit needs a spatially uniform distribution of ammonia, at low costs in terms of unit pressure loss. This makes common industrial mixing units prohibitively expensive.

Previous designs of the urea mixer (ref. Fig. 7) have been added onto the engine downstream of the exhaust receiver as an independent unit, piped together with a standard exhaust receiver and a separate SCR unit. As there is large mixing capacity available in the exhaust receiver, due to the unsteady nature and large gradients in velocity, a design which benefits from this is proposed.

As such, the design is expected to have significantly lower pressure losses at the same level of mixing as traditional designs. Even more, the design has the potential to have lower pressure losses than standard exhaust receivers. The proposed design can be seen in Fig. 9 for a four-cylinder engine.

The four pipes feeding the unit can be seen at the top. In the centre of the unit, a straight open-ended pipe is located. At the right end of the central pipe, an ‘anti swirler’ is fitted. The gas leaves the unit to the right. As the exhaust gas is injected tangentially into the unit, a strong swirling flow forms inside. Owing to this, a low pressure is obtained centrally in the left region of the unit. As the flow passes through the anti swirler, the tangential momentum of the gas is recovered as static pressure. This sets up a pressure gradient across the cen-
Fig. 9: Proposed design of a urea mixer. Flow enters tangentially into the mixing chamber from the cylinders via separate runners (a). While swirling, the flow moves upwards, but loses its swirl as it passes through the vanes at (b). Due to the loss of swirl, static pressure is recovered leading to higher pressure at (c) than in the centre of the bottom of the mixing chamber. This causes reversed flow in the centrally mounted pipe. Urea is injected at (d) and evaporates in the non-swirling flow in the central pipe. The urea seeded flow leaves the pipe in the bottom of the chamber and mixes with the newly injected exhaust gas.

Fig. 10: A snapshot from a large eddy CFD simulation of the mixing of a scalar, representing urea. The scalar is injected in the central pipe and mixes with exhaust gas during its way to the outlet.

To verify the concept and investigate the extent of mixing, a large eddy CFD simulation was performed. The four inlets were fed with unsteady mass flows representative of an S50ME engine at full load. A snapshot from the simulation can be seen in Fig. 10. A pressure drop from this design is expected to be low, as flow pathways are kept large, and momentum from the individual cylinder’s high speed jets are converted into static pressure, in a manner which is not present in standard exhaust receivers.
**Conclusion**

The application of selective catalytic reduction on an MAN B&W two-stroke diesel engine has been demonstrated by MAN Diesel & Turbo and Hitachi Zosen Corporation. It has been concluded that the SCR offers a degree of NOx reduction that ensures IMO Tier III operation. A low-load method provides the desired minimum operation temperature which suppresses undesired precipitation of ammonium bisulphate in the catalyst elements. Additionally, it has been found that the newly developed engine control system is able to handle all aspects of IMO Tier III operation: heating of the system, deceleration/acceleration and start/stop of the SCR system.

The service installation has revealed that the data obtained on the test bed can be reproduced in service. Tier III compliance has been demonstrated, and it has also been shown that the low-load method is applicable. However, the service installation has also shown that attention needs to be paid to issues related to HFO operation. Until now corrosion of the SCR system and accumulation of ABS in the exhaust gas boiler have appeared.

From the experience obtained in connection with the test bed and the service installation, the following critical parameters for a successful technical solution have been identified.

From the engine side:
- Pre-turbine SCR for the highest possible temperature
- Low-load method to ensure correct temperature
- Engine control system.
- From the SCR system side:
  - Urea injection and mixing
  - SCR elements to ensure HFO operation
  - SCR control system
  - Proper installation.
EGR Application for Tier III

Since the ratification of the IMO Tier III criteria for NO\textsubscript{x} emissions from large marine diesel engines in emission control areas (ECAs), marine engine manufacturers worldwide have been challenged to develop new measures to reduce NO\textsubscript{x}. The extent of the necessary measures to reduce NO\textsubscript{x} by up to 80%, in order to meet the IMO NO\textsubscript{x} criteria from 1 January 2016, is beyond well-known adjustments of the combustion process in two-stroke diesel engines. NO\textsubscript{x} reductions of this magnitude on two-stroke diesel engines require “add-on” technologies such as exhaust gas recirculation (EGR) or selective catalytic reduction (SCR) as described above.

In 2004, MAN Diesel & Turbo (MDT) started the first test program with EGR on the large 4T50ME-X two-stroke diesel test engine in Copenhagen, in order to verify the effect of EGR. Since the 1970s, the effect of EGR on smaller four-stroke diesel engines used in the automotive sector has been known as a very efficient means to reduce NO\textsubscript{x} in combustion engines. The HFO burned in large marine engines is a challenge when using EGR, due to the presence of a high sulphur content and a high content of solids. Thus, a wet scrubber was introduced in the EGR system.

In parallel with the EGR investigation on the 4T50ME-X test engine, MAN Diesel & Turbo planned to make a service test on a ship in order to investigate the long-term effects on the engine components. In March 2010, a retrofit EGR system was installed on a 10MW 7S50MC Mk 6 engine on board the A. P. Moeller Maersk 1,100 teu container vessel Alexander Maersk.

The following describes the investigation and testing that MAN Diesel & Turbo has completed with EGR on large two-stroke diesel engines.

EGR investigation on 4T50ME-X Engine parameter study

Several comprehensive EGR test programs have been carried out on the 4T50ME-X test engine to investigate the mechanism of different variations of engine parameters when running with EGR.

The study of engine parameter variations during EGR operation revealed the following effects on SFOC and emissions, as also shown in Table 6:

**Effects on SFOC**
- Increased \( P_{\text{comp}} / P_{\text{scav}} \) ratio has a positive impact on the SFOC penalty
- Increased \( P_{\text{hyd}} \) has a positive impact on the SFOC penalty
- Increased \( P_{\text{scav}} \) has a positive impact on the SFOC penalty
- Increased \( T_{\text{scav}} \) has a negative impact on the SFOC penalty.

**Effects on NO\textsubscript{x}**
- Increased \( P_{\text{scav}} \) has a slightly positive effect on NO\textsubscript{x}
- Increased \( P_{\text{hyd}} \) has a moderately negative effect on NO\textsubscript{x}
- Increased \( P_{\text{comp}} / P_{\text{scav}} \) has a slightly negative effect on NO\textsubscript{x}
- Increased \( T_{\text{scav}} \) has a slightly negative effect on NO\textsubscript{x}.

The reduced energy to the turbine side of the turbocharger, up to around 40%, when operating the EGR system, results in reduced scaveng air pressure and hereby negative effects on the SFOC. This highlights the need for compensating means as utilisation of cylinder bypass to compensate the decrease in the scaveng air pressure. Fig. 11 shows the two very different operating areas for the compressor running with and without EGR, corresponding to utilisation of a turbocharger cut-out solution. As can be seen from Fig. 12, the heat release is only slightly affected by EGR. Increased hydraulic injection pressure can compensate for reduced heat release in the early part of the combustion.

Effects on CO:
- Increased \( P_{\text{hyd}} \) has a significantly positive effect on CO
- Increased \( P_{\text{comp}} / P_{\text{scav}} \) has a moderately positive effect on CO
- Increased \( P_{\text{comp}} / P_{\text{scav}} \) has a moderately positive effect on CO
- Increased \( T_{\text{scav}} \) has a moderately negative effect on CO.
Test results from engine parameter variations at 75% engine load (auxiliary power for EGR lower, separator and pumps are not included in dSFOC)

<table>
<thead>
<tr>
<th>EGR level</th>
<th>NOx (g/kWh)</th>
<th>dSFOC (g/kWh)</th>
<th>CO (g/kWh)</th>
<th>Pmax (bara)</th>
<th>EGR rate(%)</th>
<th>O2 (vol. %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No EGR</td>
<td>17.8</td>
<td>0</td>
<td>0.65</td>
<td>152</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>Max. EGR</td>
<td>2.3</td>
<td>+4.9</td>
<td>4.17</td>
<td>151</td>
<td>39</td>
<td>16.0</td>
</tr>
<tr>
<td>EGR ref.</td>
<td>3.7</td>
<td>+3.0</td>
<td>2.57</td>
<td>151</td>
<td>36</td>
<td>16.8</td>
</tr>
<tr>
<td>Incr. Pcomp/Pscav</td>
<td>4.0</td>
<td>+2.5</td>
<td>2.18</td>
<td>156</td>
<td>36</td>
<td>16.8</td>
</tr>
<tr>
<td>Incr. Ptest</td>
<td>4.2</td>
<td>+2.8</td>
<td>1.83</td>
<td>151</td>
<td>37</td>
<td>16.6</td>
</tr>
<tr>
<td>Incr. Pscav</td>
<td>3.6</td>
<td>+1.9</td>
<td>2.12</td>
<td>156</td>
<td>37</td>
<td>16.6</td>
</tr>
<tr>
<td>Incr. Tscav</td>
<td>3.9</td>
<td>+3.6</td>
<td>2.82</td>
<td>156</td>
<td>34</td>
<td>16.8</td>
</tr>
<tr>
<td>Tier III setup</td>
<td>3.4</td>
<td>+0.6</td>
<td>1.34</td>
<td>157</td>
<td>41</td>
<td>16.2</td>
</tr>
</tbody>
</table>

Table 6

Fig. 11: Turbocharger compressor maps running the engine with and without EGR

EGR Tier III confirmation test

The investigation on the 4T50ME-X test engine has shown that IMO Tier III NOx compliance is achievable by the use of high pressure EGR solely. A cycle value below 3.4 g/kWh of NOx was obtained, and also the not-to-exceed (NTE) level of 5.1 g/kWh of NOx at each engine load point 25, 50, 75 and 100% was proven during the test, see Fig. 13.

Fig. 12: Heat release running with and without EGR

EGR scrubber performance

Recently, an EGR scrubber test program was carried out on the 4T50ME-X test engine in order to investigate the influence on wet scrubbing efficiency by variation of different parameters in the scrubbing process.

The purpose of the EGR scrubber is to protect the combustion chamber parts as well as other exposed engine components from sulphuric acid and parti-
cles from the exhaust gas when burning HFO with a high sulphur content.

The parameters varied and were as follows:
- Water flow in the scrubber
- Pre-scrubber flow variations
- pH variations
- Variations of internal hardware parts in the scrubber.

The investigation showed that the wet scrubbing process chosen is a robust and efficient way to clean the exhaust gas. Results from the test showed the following overall numbers:
- Up to 98% SO$_2$ removal – typical value: 90%
- Up to 92% PM removal (ISO8178) – typical value: 70-80%.

The SO$_2$ removal in the scrubber process showed a clear correlation with the amount of dosed NaOH in the scrubber water, and hereby the pH value entering the scrubber.

As shown in Fig. 15, analyses of the chemical composition of the particles before the scrubber, after the scrubber and after the turbine show that the scrubber removes all ashes and elemental carbon from the exhaust gas. The presence of sulphur after the scrubber originates from small droplets of dissolved Na$_2$SO$_4$ carried over from the scrubber water and H$_2$SO$_3$ and H$_2$SO$_4$ droplets created from the remaining part of SO$_2$ and the SO$_3$.

Fig. 15 shows the PM reduction in the scrubber during a test program completed in August 2011. As can be seen from the figure, the PM removal is between 60 and 95% which is better than what is normally seen in after-treatment scrubbers. It is expected that the improved scrubber performance (compared to normal after-treatment scrubbers) is caused by the fact that the properties of the particulate matter upstream the turbine is different from the properties of particulate at ambient conditions.

![PM reduction at 75% load](image)

![Chemical composition of PM](image)
The conclusion from the wet scrubber test is as follows:

- The SO$_2$ removal is good and significantly influenced by the added NaOH amount
- PM removal is good and only slightly influenced by variations in the hardware internals
- Ash and elemental carbon are almost totally removed in the scrubber
- Water carry-over from the EGR scrubber should be avoided due to the risk of contamination by Na$_2$SO$_4$ from the scrubber water.

**EGR service test**

A service test of the EGR process and components is an important task in the development of the future EGR engines. Engine condition as well as conditions of the EGR components is necessary to follow and develop through thousands of running hours. Currently, one EGR service test is ongoing and another service test is under preparation.

**Service test on Alexander Maersk**

The main objective of the service test, which is still ongoing, is mainly to investigate the long-term impact on the engine during EGR operation.

The EGR service test objectives are to:

- Investigate the impact of EGR operation on engine components: cylinder liner, piston, piston rings, piston rod, cylinder cover, exhaust valve, etc. when burning HFO with a high content of sulphur
- Investigate impact on the EGR components
- Hand over operation of the EGR system to the ship crew in order to get feedback on operation of the system, in order to adjust the system for easy, reliable and safe operation.

Currently, the EGR system on board Alexander Maersk has been in operation close to 1,200 hours with the engine running on HFO with 3% sulphur. NO$_x$ is reduced by more than 50%, as shown in Fig. 16. The EGR system is currently operated by the ship crew. The EGR system is a push button system controlled from the engine control room, except for the separator in the Water Treatment System (WTS), which has to be started on-site by the crew.

The thermodynamic performance of the EGR components was successfully tested, and the EGR components fulfilled the expected performance. Commissioning of the EGR system in automatic mode was also successfully completed.

Until now, the combustion chamber components and the exhaust gas path are not negatively affected by EGR operation. Fig. 17 shows the piston rings before and after approx. 900 running hours in EGR operation.

![Fig. 16: Measurements of NO$_x$ reduction on board Alexander Maersk during a performance test](image)
The service test, which is still ongoing, has been quite challenging due to the HFO operation with a high sulphur content. The challenges have mainly been related to the following issues:

- Corrosion of non-stainless components. Heavy corrosion has been experienced on the EGR cooler housing, EGR cooler element, EGR blower wheel, drainers, EGR pipe and separator in the WTS system.
- Difficulties with controlling the dosing of the correct amount of NaOH.
- Water carry-over from the scrubber system, resulting in heavy deposits in the EGR system.

In order to deal with corrosion challenges, the following components have been exchanged with stainless steel: the EGR blower wheel, drainers and some valves in the WTS system. The EGR cooler element will be exchanged with a stainless steel element. In addition, a comprehensive repair of the EGR cooler housing and the EGR pipe from the blower to the connection on the charge air pipe has been completed due to insufficient coatings.

The service test has gained a lot of important learning and information on what the challenges are when running EGR on an HFO burning two-stroke marine diesel engine, as can be seen in Fig. 18. Corrosion of EGR components and deposits in the EGR system are important to target. Until this state of the service test, the engine components are not affected by high pressure EGR operation.
Preparation of service test on new-building with 6S80ME-C9.2

The newest target in the development of MAN Diesel & Turbo’s two-stroke EGR engines is a full Tier III compliant prototype with the EGR components integrated into the engine structure. With this project, MAN Diesel & Turbo targets larger two-stroke EGR engines with more than one turbocharger utilising TC cut-out for high engine efficiency in future ECA areas.

The objectives of the service test are:

- Maturing of the EGR engine concept for IMO Tier III compliance
- Monitoring combustion chamber parts and other exposed engine parts under realistic conditions
- Monitoring of the EGR components’ operational conditions under realistic operating conditions, i.e. during burning of HFO
- Education of crew to make reliable operation of the EGR system and gain experience for future instruction books, education and support
- Identifying simplification and cost down potentials.

The design experience from the project is to extend the EGR-2 principle throughout the MAN Diesel & Turbo engine programme.

As can be seen from Fig. 19, the 6S80ME-C9 EGR engine has one small turbocharger and one large turbocharger and cut-out facilities for the small turbocharger. The engine will run in the following modes:

- Non-ECA operation (blue and purple lines): both turbochargers are working in parallel under normal conditions supplying the engine with the necessary scavenge air. At low-load TC cut-out, it can be utilised to save fuel.
ECA operation – Tier III (blue and green lines): the small turbocharger is cut out to compensate the reduced exhaust gas amount, and the EGR blower is running to supply exhaust gas into the scavenge air receiver. The pre-scrubber and scrubber clean the EGR before the exhaust gas enters the scavenge air receiver. The EGR cooler has a double function and acts as an EGR cooler in this mode and as a normal charge air cooler in non-ECA mode.

The vessel newbuilding No. 2358 is the last delivery of the APMM C-class series, see Fig. 20, from Hyundai Mipo Shipyard in Ulsan Korea. The ship is equipped with MAN B&W 6S80ME-C9 engines and an MHI waste heat recovery system de-rated from 27 MW to 23 MW.

The engine is planned for shop trial in August/September 2012, including full commissioning of the EGR system, including an Alfa Laval water treatment system. The engine will be certified by class ABS. The technical file will be according to the normal Tier II certificate. However, knowledge is gathered to make a proposal for a Tier III certification procedure.

The sea trial will take place in January 2013, and subsequently EGR commissioning will be carried out when the vessel is in service operation.

After delivery in early 2013, the vessel will go into service on the West Africa - Far East route. Even though the vessel would not sail in ECAs, it will be operated in ECA mode for 20% of the time. For the remaining time, it is agreed to operate the engine with low EGR rates – to allow service time on the EGR components and to fuel optimise the operation. The EGR service test period is planned to be for three years until early 2016, when the NOX Tier III limits enter into force.

HHI-EMD will produce the 6S80ME-C9.2 EGR engine, and the following engine modifications will be made:

- Sequential turbocharging
- EGR cooler and scrubber module in duplex material from a local producer based on MAN Diesel & Turbo design
- High-efficient EGR blowers
- Stainless steel coolers with dual functionality
- Gas control valves
- Changed components such as exhaust receiver, scavenge air receiver and galleries
- The main engine outline is only modified slightly at the EGR-2 module – keeping the engine foot print unchanged
- Control system modifications.

Besides integrated EGR components on the engine, as can be seen in Fig. 21, and related engine modifications, the following installation work will be carried out by HHI Shipbuilding Division:

- Installation of NaOH and EGR sludge tanks
- Installation of water treatment system
- Installation of frequency converters for EGR blowers
- Installation of stainless piping for scrubber water handling
- Extended central cooling water capacity
- Electrical installation
- Software update of control alarm and monitoring system for tank monitoring
- Software update of power monitoring system for waste heat recovery and ME heat capacities.

MAN Diesel & Turbo highly appreciates the close corporation with leading engine builders, shipyards and shipowners for this strategic important prototype project.
Water treatment system (WTS)

MAN Diesel & Turbo is heavily involved in the development of water treatment systems (WTS) for both EGR and SOX scrubbing systems. The WTS is essential for running the EGR system, and compliance with IMO criteria for wash water discharge is highly prioritised. Over the last couple of years, Alfa Laval has, in cooperation with MAN Diesel & Turbo, developed a complete water treatment system for the EGR engine. Extensive testing and investigation on how to clean scrubber water in an efficient and reliable way have been carried out successfully.

WTS system layout and functionality

The EGR WTS system is an important part of operating the EGR system because the contaminated scrubber water needs to be cleaned for soot particles to avoid clogging up the system. Moreover, the water generated during combustion which is condensed in the EGR cooler, needs to be discharged to the sea, in a clean condition, to avoid large storage tanks on board.

During the development of the WTS, it became clear that the aim should go for a unit solution that is simple to install for the shipyards, like a “plug and play” solution. Much functionality is hereby included in the WTS system, i.e. the NaOH dosing, water flow control and discharge control.

Fig. 21: integrated design of EGR unit (orange) on a 6S80ME-C9 engine
In order to make installation highly flexible, the WTS module is divided into two units:

- WTS1 module, see Fig. 22, comprises the separators, scrubber pumps, NaOH dosing, etc., to be placed wherever there is space in the ship
- WTS2 module (collecting tank module) for transportation of the scrubber water from engine site to the WTS1 module to be placed close to the engine below the EGR unit on the engine.

The WTS system is a necessary EGR auxiliary system for EGR operation because of the following functionalities:

- Controlling of the correct water supply to the EGR scrubber
- Reliable and clean conditions in the scrubber system
- Correct dosing of NaOH
- Controlling of the salt concentration in the scrubber water
- Compliance with IMO regulation for wash water discharge
- Minimal pumpable sludge production.

As shown in Fig. 23, the WTS system is divided into modules. Module 1 comprises separators for both cleaning of the scrubber water supplied to the EGR unit and for cleaning of the discharge water. All water supplied to the EGR scrubber is cleaned in order to ensure reliable operation without any clogging up of deposits scaling up in the scrubber system. Cleaning of the discharge water is carried out on the cleaned scrubber from the scrubber water cleaning separators. The WTS1 module controls the amount of scrubber water in the system by either discharge of water or addition of fresh water. The
WTS system ensures compliance with IMO wash water criteria in all operation cases.

The following parameters will define the engine requirements to the WTS system:

- Inlet scrubber water flow
- Inlet scrubber water pressure
- Inlet scrubber water temperature
- Quality of inlet scrubber water
  - pH value
  - salt concentration
  - solids fraction
- Draining capacity.

The current development is aiming at defining all necessary specific values for the above-mentioned parameters.

**EGR high-speed blower**

In order to improve the EGR process, in particular reduction of the additionally needed auxiliary power, MAN Diesel & Turbo has been involved in the development of a new high-speed EGR blower with a significantly higher thermodynamical efficiency than former designs.

The high-speed EGR blower is based on a radial turbo compressor wheel running at 2-3 times higher speeds than a conventional radial b-wheel.

MAN Diesel & Turbo is currently collaborating with Siemens Turbo Systems on developing EGR blowers for the two 6S80ME EGR prototype service test. Besides, MAN Diesel & Turbo is also developing an in-house solution in order to ensure more than one supplier of EGR blowers.

The requirements for a high-speed EGR blower are:

- High efficiency over wide flow range
- Fast dynamic flow response
- Corrosion resistant materials
- Reliable, well-known technologies
- Lube oil journal and thrust bearing
- Compact design
- Flange mounting
- Leakage proof by use of sealing air
- Simple control interface
- Integrated monitoring of operation condition.

Fig. 24 shows the required compressor map for an EGR blower from Siemens, including operational points for different engine loads. Tests have shown that requirements were met satisfactorily.
Fig. 25 shows the EGR blower produced for testing on the 4T50ME-X test engine. Specifications of the EGR blower are as follows:

- **Power**: 200 kW
- **Thermodynamic efficiency**: 0%
- **Pressure lift**: 600 mbar
- **Mass flow**: 4 kg/s (at 31°C inlet temperature)
- **Weight**: 600 kg
- **Lube oil flow**: 60 l/min
- **Cooling water flow**: approx. 2 m³/h.

The EGR blower has been tested on the test bed at ambient conditions with satisfying performance figures, and issues with surging at a high pressure ratio against a closed valve at the blower outlet was tested not critical. The next step of testing will be a blower performance and controlling test on the MDT 4T50ME-X test engine planned for April 2012. Subsequently, a test on Alexander Maersk will be conducted. Currently, two sizes of the Siemens high-speed EGR blowers are available, covering engines from approx. 5-23 MW.
Conclusion

As can be seen from the above, the EGR application on two-stroke MAN B&W engines has, over the last decade, developed from a basic idea on how to reduce NOx emissions to a dedicated design, suitable for application on the engine in standard configuration.

The development process has ensured dedicated development of:

- Water spraying systems for pre-cooling of exhaust gas
- Wet coolers capable of withstanding SO2, SO3, and H2SO4 condensation
- Scrubbers with very high SO2 and particulate emission removal capacity
- Compact high-speed and high-efficiency EGR blowers
- Water treatment systems capable of removing particulate matter efficiently, and clean water to suitable discharge level
- Control systems capable of securing simple push-button operation of the EGR system
- Control strategies securing optimal engine performance in both Tier II areas and in Tier III ECA areas.

This makes MAN Diesel & Turbo confident that the EGR system application will be available in due time before 2016 for the complete engine range.
All data provided in this document is non-binding. This data serves informational purposes only and is especially not guaranteed in any way. Depending on the subsequent specific individual projects, the relevant data may be subject to changes and will be assessed and determined individually for each project. This will depend on the particular characteristics of each individual project, especially specific site and operational conditions. Copyright © MAN Diesel & Turbo. 5510-0125-00pp Aug 2012 Printed in Denmark.