EGR application to meet future emissions requirements

NOx The measures necessary to reduce NOx by up to 80% under IMO regulations taking effect on January 1st 2016 go beyond well-known adjustments of the combustion process in two-stroke diesel engines. The exhaust gas recirculation (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 the engines in standard configuration. To verify the effect, MAN Diesel & Turbo started the first test programme on its large 4T50ME-X two-stroke diesel test engine in 2004.

Since the 1970s, the use of EGR on smaller four-stroke diesel engines in the automotive sector has been known as a very efficient means to reduce NOx. The HFO burned in large marine engines presents a challenge when using EGR due to the high concentration of sulphur and solids, so a wet scrubber was introduced in the EGR system.

In parallel with the EGR investigation of the 4T50ME-X test engine, MAN Diesel & Turbo planned to conduct a service test on a ship to investigate the long-term effects on the engine components. In March 2010, a retrofit EGR system was installed on a 10 MW 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.

Wet scrubber performance

In order to investigate the influence on wet scrubbing efficiency by variation of different parameters in the scrubbing process, an EGR scrubber test programme was carried out on the 4T50ME-X test engine. The purpose of the EGR scrubber is to protect the combustion chamber parts as well as other exposed engine components from sulphuric acid and particles 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 thereby the pH value entering the scrubber.

Figure 1 shows the PM removal in the scrubber during a test programme completed in August 2011. As can be noted, the PM removal is between 60 and 95%, which is better than what is normally seen in after-treatment scrubbers. It is thought that the improved scrubber performance (compared with normal after-treatment scrubbers) is caused by the properties of the particulate matter upstream the turbine being different from those at ambient conditions.

As shown in Figure 2, analyses of the chemical composition of the particles before the scrubber, after the scrubber and after the turbine show that the scrubber removes all ash and elemental carbon from the exhaust gas. The presence of sulphur after the scrubber comes from small droplets of dissolved Na_2SO_4 carried over from the scrubber water and H_2SO_3 and H_2SO_4 droplets created from the remaining part of SO_2 and the SO_3.

The conclusion from the wet scrubber test is as follows:

- The SO_2 removal is good and significantly influenced by the added NaOH,
- 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,

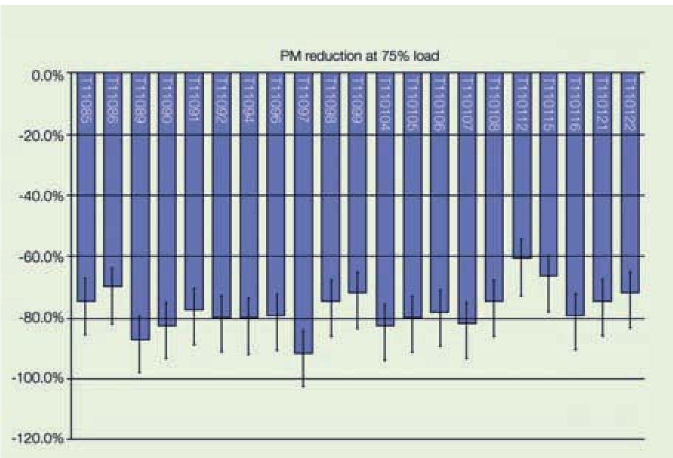

Figure 1: PM reduction over scrubber

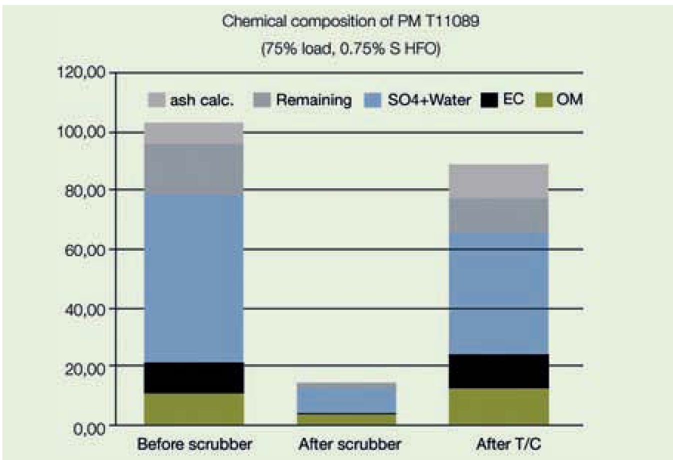

Figure 2: Chemical composition

- Water carry-over from the EGR scrubber should be avoided due to the risk of contamination by Na_2SO_4 from the scrubber water.

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 sulphur content,
- Investigate the impact on the EGR components,
- Hand over operation of the EGR system to the ship's crew for feedback in order to adjust the system for easy, reliable and safe operation.

Currently, the EGR system on board the *Alexander Maersk* has been in operation for nearly 1,200 hours, with the engine running on HFO with 3% sulphur. NOx is reduced by more than 50%, as shown in Figure 3. The EGR system, currently operated by the crew, is a push-button system monitored 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.
So far, the combustion chamber components and exhaust gas path have not been negatively affected by EGR operation.
The service test has been quite challenging due to the HFO operation with a high sulphur content. The main reasons for this are:

- 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 EGR blower wheel, drainers and some valves in the WTS system have been exchanged with stainless steel.
The EGR cooler element will be exchanged with a stainless steel element in due course. 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 provided a lot of important knowledge and information on the challenges when running EGR on an HFO-burning two-stroke marine diesel engine. Corrosion of EGR components and deposits in the EGR system are important to target. Up to this state of the service test, the engine components have not been affected by high-pressure EGR operation.

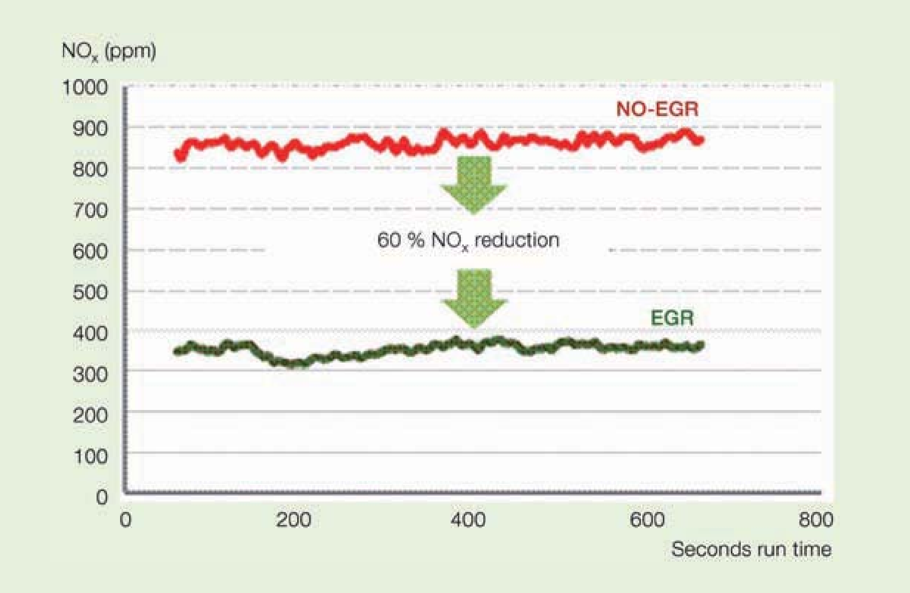

Figure 3: NOx reduction on board *Alexander Maersk* during a performance test

Preparation of service test on newbuilding with 6S80ME-C9.2

The newest object 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's 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 the EGR components' operational conditions under realistic operating conditions, i.e. during burning of HFO,
- Educating crew to make operation of the EGR system reliable and to gain experience for future instruction manuals, teaching and support,
- Identifying simplification and cost-down potentials.

The design experience from the project is to be used to extend the EGR-2 principle throughout the MAN Diesel & Turbo engine programme.
As can be seen from Figure 4, 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 for 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 from Hyundai Mipo Shipyard in Ulsan, South 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 and an Alfa Laval water treatment system. The engine will be certified by the classification society ABS. The technical file will be in accordance with the normal Tier II certificate. However, knowledge is being gathered to make a proposal for a Tier III certification procedure.
The sea trial will take place in January 2013, and subsequent 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 it will not sail in ECAs, it will operate in ECA mode 20% of the time. For the remaining time, it has been agreed to operate the engine with low EGR rates to allow service time on the EGR components and to fuel-optimise the operation. The planned duration of the EGR service test period is 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,

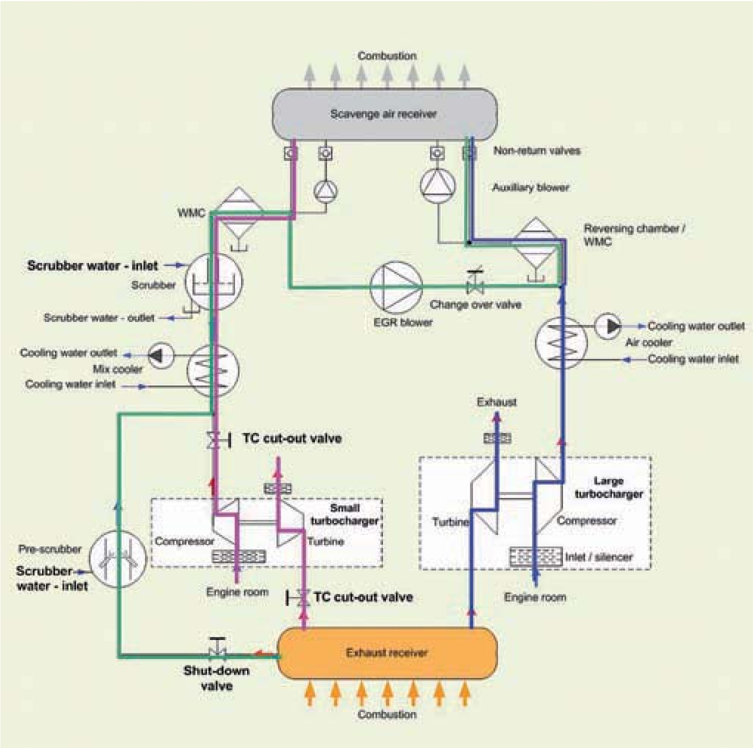

Figure 4: EGR system diagram for a 6S80ME-C9 with two turbochargers

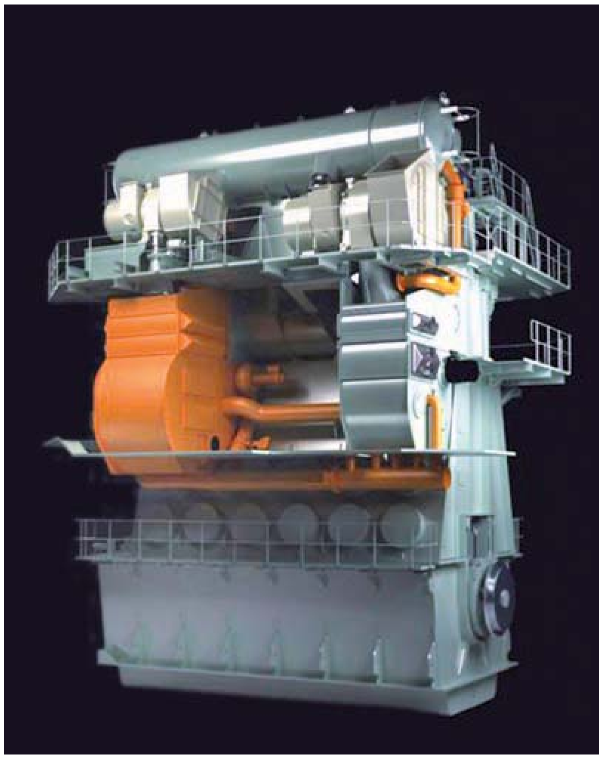

Figure 5: Integrated design of EGR unit (orange)

- High-efficiency 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 modified only slightly at the EGR-2 module – keeping the engine footprint unchanged,
- Control system modifications.

Besides integrated EGR components on the engine, as can be seen in Figure 5, and related engine modifications, the following installation work will be carried out by HHI's (Hyundai Heavy Industries) shipbuilding division:

- Installation of NaOH and EGR sludge tanks,
- Installation of water treatment system,
- Installation of frequency converters for EGR blowers,
- Installation of stainless steel 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.

Water treatment system (WTS)

MAN Diesel & Turbo is also heavily involved in the development of water treatment systems for both EGR and SOx scrubbing systems. The WTS is essential for running the EGR system, and compliance with IMO criteria for washwater discharge is highly prioritised. Over the last couple of years, Alfa Laval has developed, in cooperation with MAN Diesel & Turbo, a complete WTS for the EGR engine. Extensive testing and investigation of 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 of soot particles to avoid clog-

ging up the system. Moreover, the water generated during combustion needs to be discharged into 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 be a unit solution that is simple for the shipyards to install, such as a "plug and play" solution. A lot of functionality is thereby included in the WTS system, i.e. the NaOH dosing, water flow control and discharge control.
To make installation highly flexible, the WTS module is divided into two units:

- WTS1 module, comprising the separators, scrubber pumps, NaOH dosing, etc., to be placed wherever there is space on the ship.
- WTS2 module (collecting tank module) for transportation of the scrubber water from the 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:

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

As shown in Figure 6, the WTS system is divided into modules. Module 1 comprises separators for cleaning both the scrubber water supplied to the EGR unit and the discharge water. All water supplied to the EGR scrubber is cleaned to ensure reliable operation without any clogging due to deposits scaling up the scrubber system. Cleaning 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 washwater criteria in all operation cases.
The following parameters will define the engine requirements of 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.

EGR high-speed blower

To improve the EGR process, particularly reduction of the additional auxiliary power needed, MAN Diesel & Turbo has been involved in the development of a new high-speed EGR blower with a thermodynamic efficiency significantly higher than former designs. The high-speed EGR blower is based on a radial turbo compressor wheel running at speeds two to three times higher 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. 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.

Specifications of the EGR blower produced for testing on the 4T50ME-X test engine 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: approximately 2 m^3/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 were not found to be critical. The next step of testing includes a blower performance and controlling test on the MDT 4T50ME-X test engine. Subsequently, a test on the *Alexander Maersk* will be conducted. Currently, two sizes of the Siemens high-speed EGR blowers are available, covering engines from approximately 5-23 MW.

Conclusion

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 the dedicated development of:

- Water-spraying systems for pre-cooling of exhaust gas,
- Wet coolers capable of withstanding SO_2, SO_3 and H_2SO_4 condensation,
- Scrubbers with very high SO_2 and particulate emission removal capacity,
- Compact high-speed and high-efficiency EGR blowers,
- Water treatment systems capable of removing particulate matter efficiently and cleaning water to a 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.