Emission Project Guide

MAN B&W Two-stroke Marine Engines

Engineering the Future – since 1758.

MAN Diesel & Turbo

Emission Project Guide

Scope

The intention of the Emission Project Guide is to give sufficient information to decide and design solutions for emission reductions at the initial stage of a project involving MAN B&W two-stroke marine engines. The information provides technical data needed for the preliminary design, including data for performance, layout, consumables, control and installation of the equipment.

The Emission Project Guide is divided in three parts:

Part 1 NO_x reduction – IMO Tier III solutions

Part 2 SO_x reduction – exhaust gas cleaning system (content to follow)

Part 3 NO_x and SO_x reduction – combined solutions (content to follow)

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.

If this document is delivered in another language than English and doubts arise concerning the translation, the English text shall prevail.

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Contents

Abbreviations

CBV	Cylinder bypass valve
CTU	Collecting Tank Unit
ECA	Emission Control Area
ECR	Engine Control Room
EGB	Exhaust gas bypass
EGR	Exhaust Gas Recirculation
EMC	Electro Magnetic Compatibility
FW	Freshwater
HFO	Heavy fuel oil
HP	High pressure
IMO	International Maritime Organisation
ISO	International Standard Organisation
LP	Low pressure
MARPOL	International Convention for the Prevention of Pollution from Ships
MCR	Maximum Continuous Rating
MDO	Marine diesel oil
MGO	Marine gas oil
NO_x	Nitrogen Oxides
RBV	Reactor bypass valve
RSV	Reactor sealing valve
RTV	Reactor throttle valve
PM	Particulate Matter
RH	Relative Humidity
S%	Sulphur content percentage in fuel oil
SCR	Selective Catalytic Reduction
SCR-DCS	SCR dosing control system
SCR-VCS	SCR valve control system
SFOC	Specific Fuel Oil Consumption
SMCR	Specified Maximum Continuous Rating
SO_x	Sulphur Oxides
T/C or TC	Turbocharger
UPS	Uninterruptible Power Supply
WMC	Water Mist Catcher
WTS	Water Treatment System
WTU	Water Treatment Unit

NO_x and SO_x rules

The international requirements on emissions of NO_x (nitrogen oxides), SO_x (sulphur oxides) and PM (particulate matter) are determined by the *MARPOL convention Annex VI – Regulations for the Prevention of Air Pollution from Ships*.

- NO_x

  According to the rules, the NO_x emission of any marine diesel engine installed in a **ship constructed on or after 1 January 2016** must not exceed the so-called Tier III level when operating inside a NO_x emission control area (NO_x ECA). For engines with an engine speed lower than 130 rpm, the Tier III level is 3.4 g/kWh. When operating outside a NO_x ECA, the engine must meet the Tier II limit of 14.4 g/kWh. Engines with an engine speed higher than 130 rpm must meet even lower limits.[1]

  Any abatement technology reducing the NO_x emission to the required level can be accepted. However, guidelines developed for this purpose must be followed.[2]

- SO_x and PM

  Emissions of SO_x and PM are regulated by the sulphur content of any fuel used on board ships. The rules of SO_x and PM **apply to all ships**, no matter the date of ship construction.

  When sailing inside SO_x emission control areas (SO_x ECA), the sulphur content must not exceed 1.0%. This limit will be reduced to 0.1% from 1 January 2015. When sailing outside SO_x ECA, the sulphur content must not exceed 3.5% until 1 January 2020 where a new limit of 0.5% sulphur is introduced.[3]

  Any abatement technology reducing the emission of SO_x and PM to a level equivalent to the emission level when using the accepted fuels will be accepted, provided the relevant guidelines are followed. [4]

1 *MARPOL Annex VI, Regulation 13*
2 *MARPOL Annex VI, Regulation 4*
3 *MARPOL Annex VI, Regulation 14*
4 *MARPOL Annex VI, Regulation 4*

1 NO_x reduction – Tier III solutions

1.1 Introduction

Two-way approach to NO_x reduction

MAN Diesel & Turbo offers two alternative methods to meet the Tier III NO_x requirement on two-stroke engines. The first method, exhaust gas recirculation (EGR), is an internal engine process to prevent the formation of NO_x by controlling the combustion process. The second method, selective catalytic reduction (SCR), is an after-treatment method using an additive to reduce the NO_x generated in the combustion process. Fig. 1.01 shows the layout of an EGR and SCR configured engine.

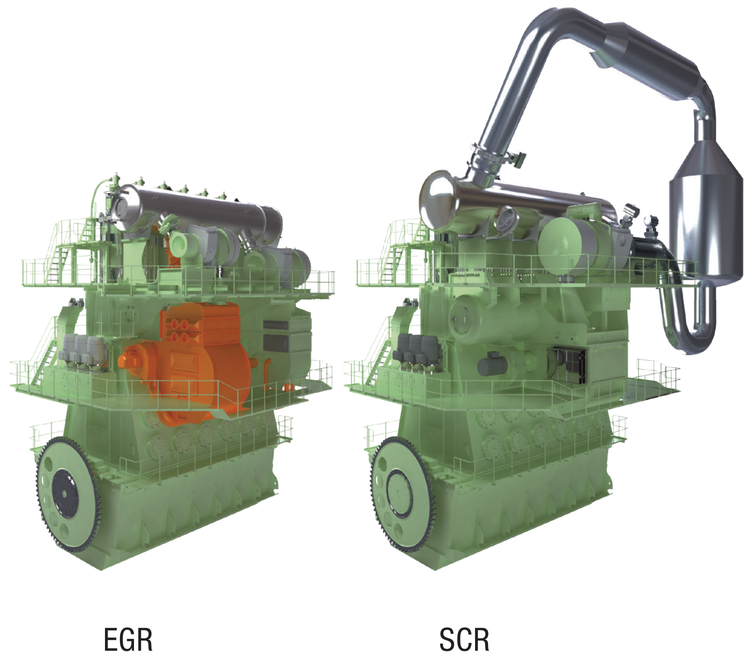

Fig. 1.01: Two-way approach for Tier III engine – EGR and SCR solutions

Influence of sulphur in fuel

As the emission control areas with Tier III requirements most likely will include low SO_x limits, the ships sailing into these areas must either run on low-sulphur fuel (0.1% in 2015) or run a SO_x scrubber process in addition to the Tier III low-NO_x mode. Both the EGR and the SCR system will be able to run on high-sulphur fuel, but in these cases the exhaust system must also be equipped with a SO_x scrubber system. When planning the Tier III installation, these conditions must be considered. In Part 3 of this guide, combined solutions with SO_x scrubber are described.

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1.2 EGR – Exhaust Gas Recirculation

1.2.1 EGR principle

Exhaust gas recirculation (EGR) is a method to significantly reduce the formation of NO_x in marine diesel engines.

In the EGR system, after a cooling and cleaning process, part of the exhaust gas is recirculated to the scavenge air receiver. In this way, part of the oxygen in the scavenge air is replaced by CO_2 from the combustion process. This replacement slightly increases the heat capacity of the scavenge air, thus reducing the temperature peak of the combustion and the formation of NO_x. The NO_x reduction is almost linear to the ratio of recirculated exhaust gas. The principle of EGR is illustrated in Fig. 1.02.

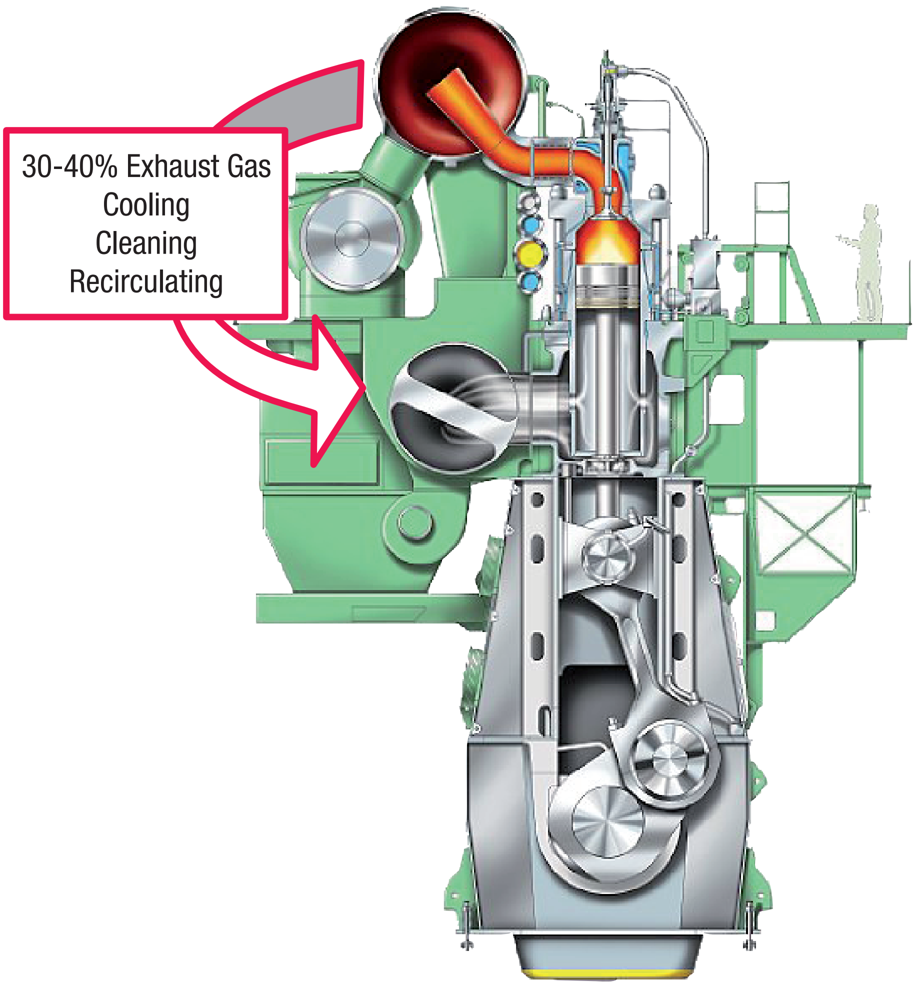

Fig. 1.02: Principle of EGR

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1.2.2 EGR system

Two different layouts are available for the EGR systems: EGR with bypass matching, normally with only one turbocharger, and EGR with TC cut-out matching, having two or more turbochargers.

Bypass matching

An EGR system with bypass matching is shown in Fig. 1.03. Two strings, a main string and an EGR string, are available to direct the scavenge air into the scavenge air receiver:

- the main string, with the capacity to lead all the scavenge air through the turbocharger compressor and the scavenge air cooler. The main string is provided with a cylinder bypass and an exhaust gas bypass (EGB).
- the EGR string, with the capacity to lead up to 40% of the exhaust gas through the EGR unit (pre-scrubber, cooler, scrubber and WMC) to a mixing point before entering the scavenge air receiver, forced by the EGR blower.

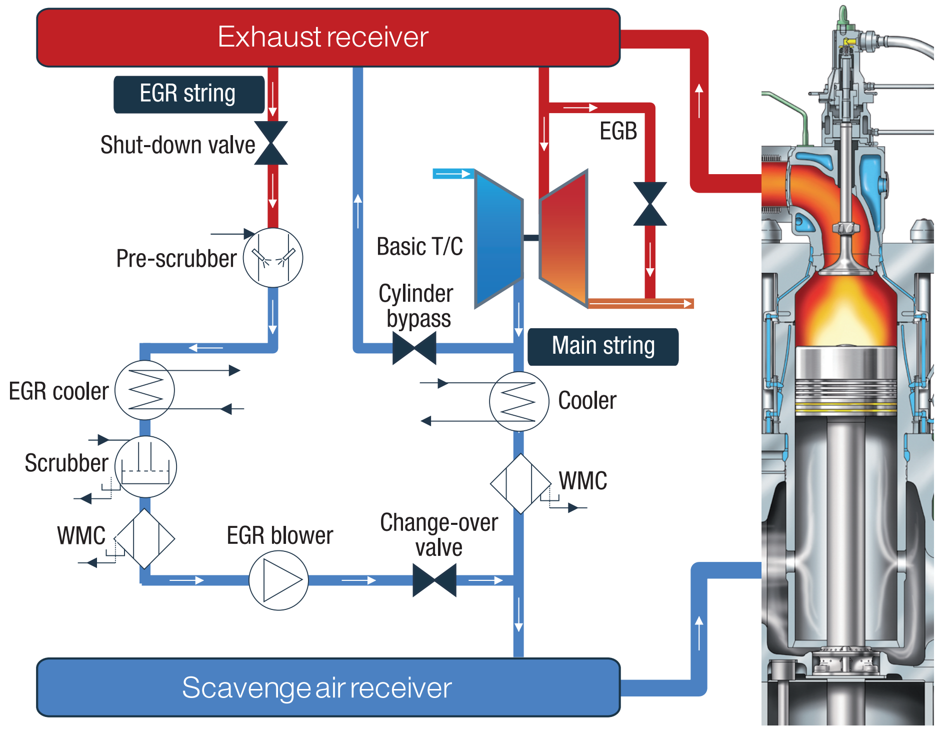

Fig. 1.03: EGR process diagram with one turbocharger

Two modes are available for this system:

- Tier II mode

  The Tier II mode is the standard mode used in non-ECAs. Only the main string is in operation, and the EGR string is kept closed by the shut-down valve. The cylinder bypass is also kept closed in this mode. At high load, the exhaust gas bypass is open to increase the efficiency of the engine.

- Tier III mode

  The Tier III mode is the mode used inside ECAs. In this mode, the EGR string is activated by opening the EGR shut-down valve and the change-over valve. The exhaust gas is led through the EGR string into the pre-scrubber, and the saturated gas passes through the EGR cooler before entering the scrubber operating with water to absorb particles, SO_x and other matters. The cleaned and cooled exhaust gas continues through a water mist catcher into the main string, forced by the EGR blower. The mixture of air and recirculated gas is finally led to the scavenge air receiver. The cylinder bypass is active in this mode to increase the scavenge air pressure and thereby reduce the SFOC.

  IMO Tier III NO_x requirements can be met in the full load range by using the EGR blower to control the EGR ratio.

TC cut-out matching

An EGR system with TC cut-out matching is shown in the diagram in Fig. 1.04. Three strings, a main string, a cut-out string and an EGR string, are available in the system to direct the scavenge air into the scavenge air receiver:

- the main string, leads up to 70% of the scavenge air through the large turbocharger (hereafter called the basic turbocharger) and the scavenge air cooler. For safety reasons the main string is provided with an exhaust gas bypass.

- the cut-out string, leads up to 40% of the scavenge air through a smaller turbocharger (hereafter called the cut-out turbocharger) and through the EGR cooler and scrubber before entering the scavenge air receiver.

- the EGR string, leads up to 40% of the exhaust gas through the EGR unit (pre-scrubber, cooler, scrubber and WMC) to a mixing point before entering the scavenge air receiver, forced by one or more EGR blowers. In this case the cut-out string is closed.

On some larger engines, a configuration with more than two turbochargers will be needed. The principle is unchanged but the number of turbochargers and EGR units is increased.

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Two modes are available for this system:

- Tier II mode

  The Tier II mode is the standard mode used in non-ECAs. Both the main string and the cut-out string are in operation with the turbocharger cut-out valves open, however, the EGR string is kept closed by the shut-down valve. From the cut-out string, compressed air passes through the EGR cooler, basically similar to a normal scavenge air cooler. From the cooler the air passes through the scrubber, which in this mode works without water supply. Finally the charge air passes through the standard water mist catcher before entering the scavenge air receiver. About 40% of the scavenge air is passed through the cut-out string, the remaining 60% through the main string.

- Tier III mode

  The Tier III mode is the mode used inside ECAs. In the EGR mode, the cut-out string is closed by the turbocharger cut-out valves and the EGR string is activated by opening the EGR shut-down valve and the change-over valve. The gas is passed through the EGR string into the pre-scrubber and the saturated exhaust gas passes through the EGR cooler before entering the scrubber, now operating with water to absorb particles, SO_x and other matters. The cleaned and cooled exhaust gas continues through a water mist catcher into the main string, forced by one or more EGR blowers. The mixture of air and recirculated gas is finally led to the scavenge air receiver. The EGR ratio is controlled by changing the flow of the EGR blower.

  The IMO Tier III NO_x requirements can be met in the full load range by using the EGR blower to control the EGR ratio.

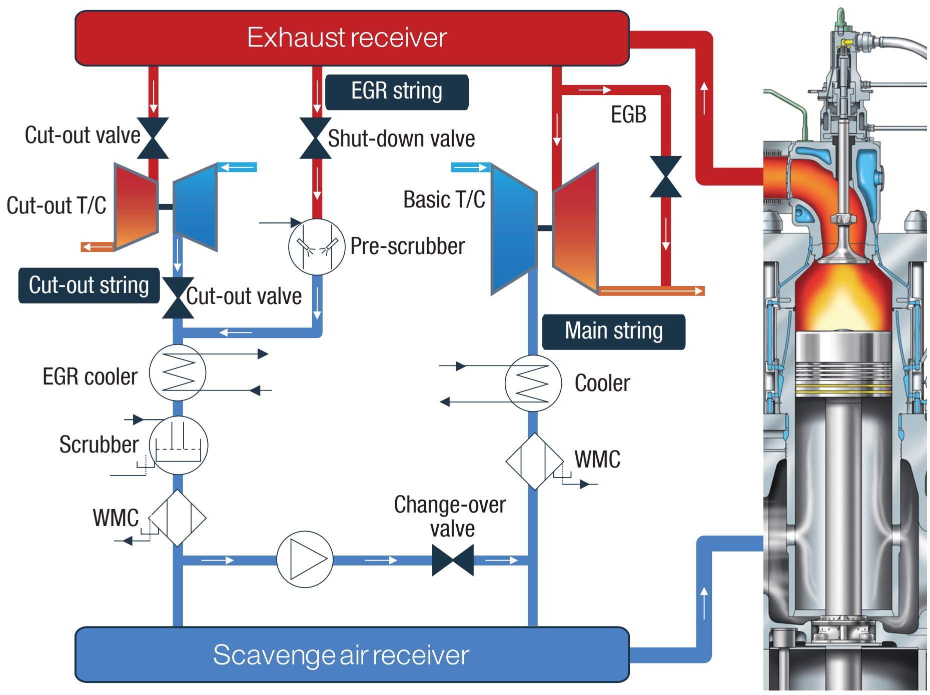

Fig. 1.04: EGR process diagram with two turbochargers

1.2.3 EGR layout

The layout of an MAN B&W EGR Tier III engine using TC cut-out matching is shown in Fig. 1.05. It illustrates the location of the EGR components integrated on the engine. The EGR water treatment system, which is not an integrated part of the engine, is described and illustrated in a separate chapter.

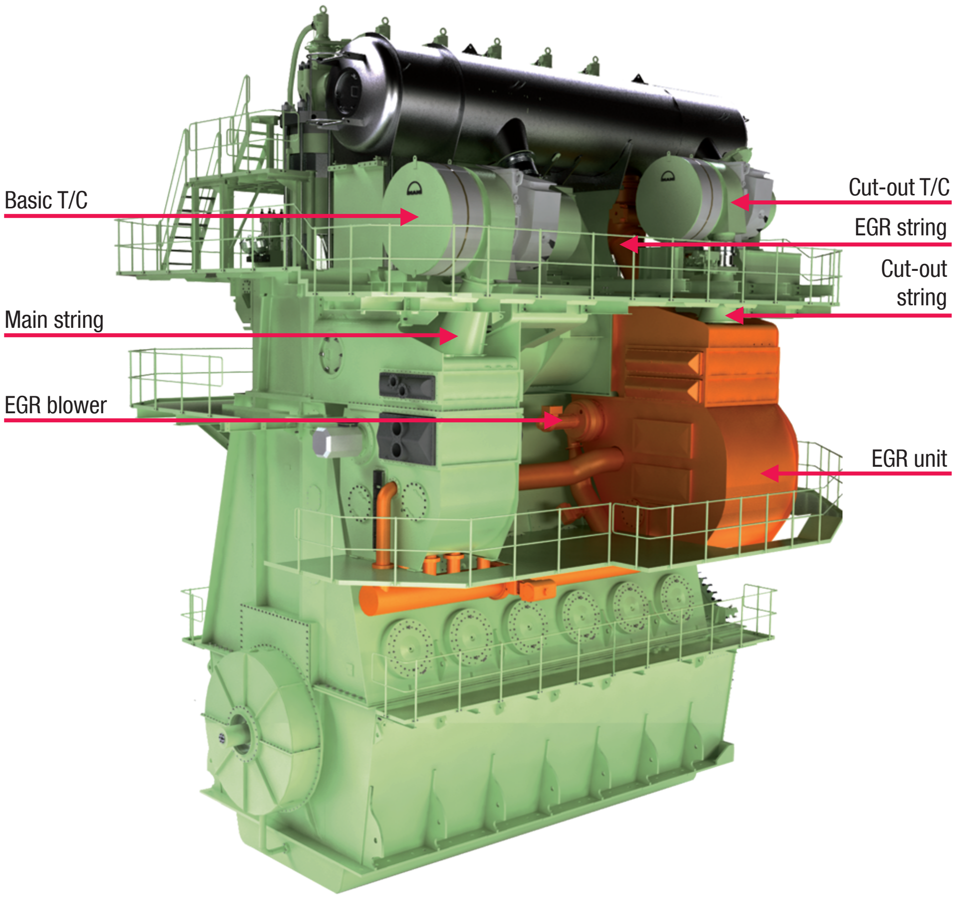

Fig. 1.05: Integrated EGR layout for two turbochargers

1.2.4 EGR configuration

Bypass matching

On an EGR system with bypass matching, the turbocharger is mounted either on the exhaust side or aft. In both cases, the EGR unit is mounted on the exhaust side. The two configurations are shown in Fig. 1.06 and 1.07.

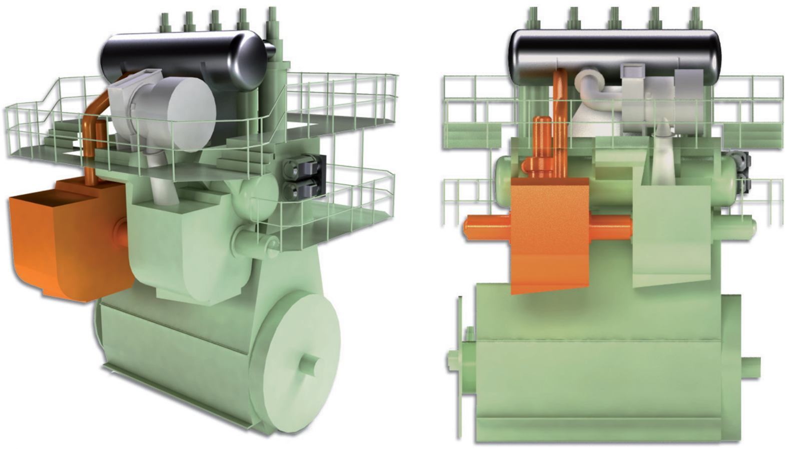

Fig. 1.06: Side-mounted turbocharger and side-mounted EGR unit

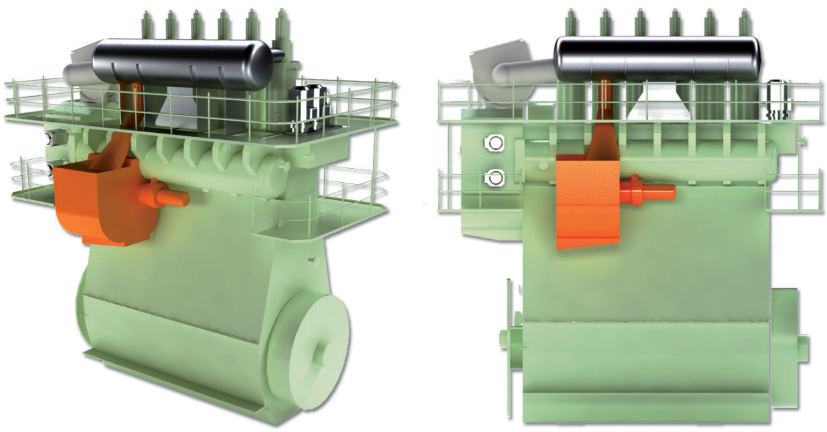

Fig. 1.07: Aft-mounted turbocharger and side-mounted EGR unit

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TC cut-out matching

The configurations of EGR systems with TC cut-out matching are shown in Figs. 8-10. The MAN B&W marine engine programme is covered by combining one or more EGR units including cut-out turbochargers with one or more basic turbochargers.

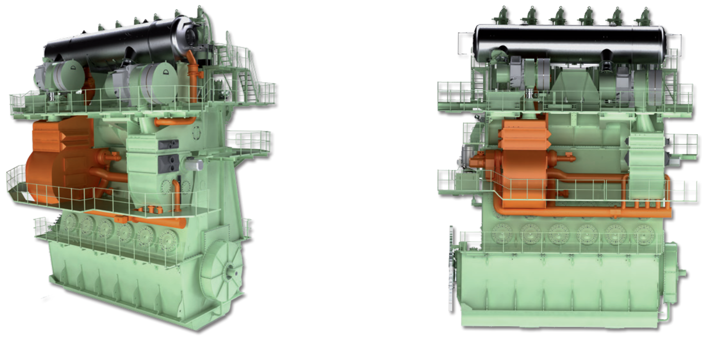

Fig. 1.08: One basic T/C, one cut-out T/C, and one EGR unit

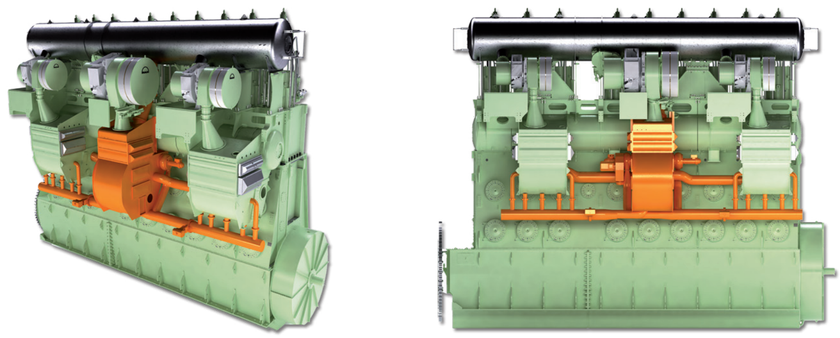

Fig. 1.09: Two basic T/Cs, one cut-out T/C, and one EGR unit

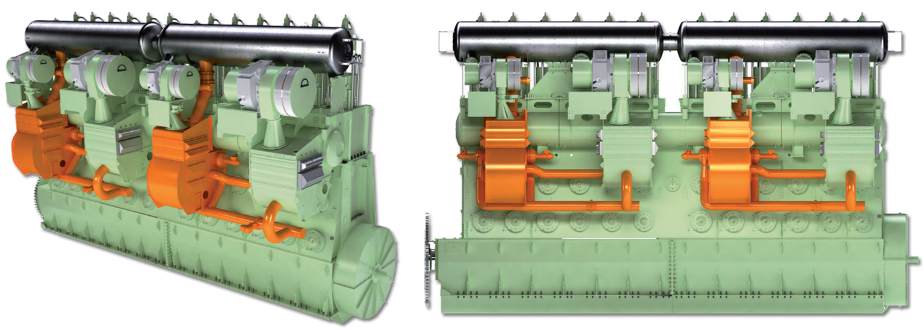

Fig. 1.10: Two basic T/Cs, two cut-out T/Cs, and two EGR units

1.2.5 Engine outline

Bypass matching

The outline of an EGR system with bypass matching is shown in Fig. 1.11 with one side-mounted turbocharger and Fig. 1.12 with one aft-mounted turbocharger.

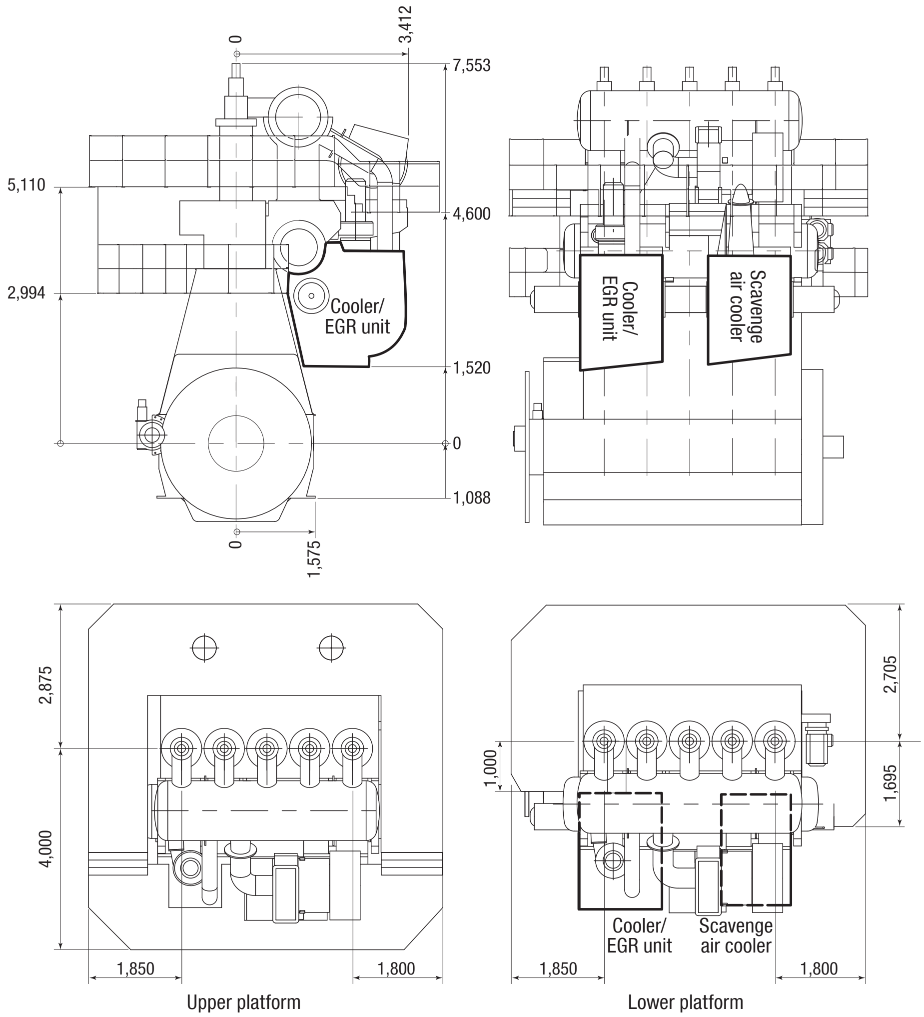

Fig. 1.11: EGR engine with one side-mounted turbocharger and EGR unit, example from 5S50ME-C

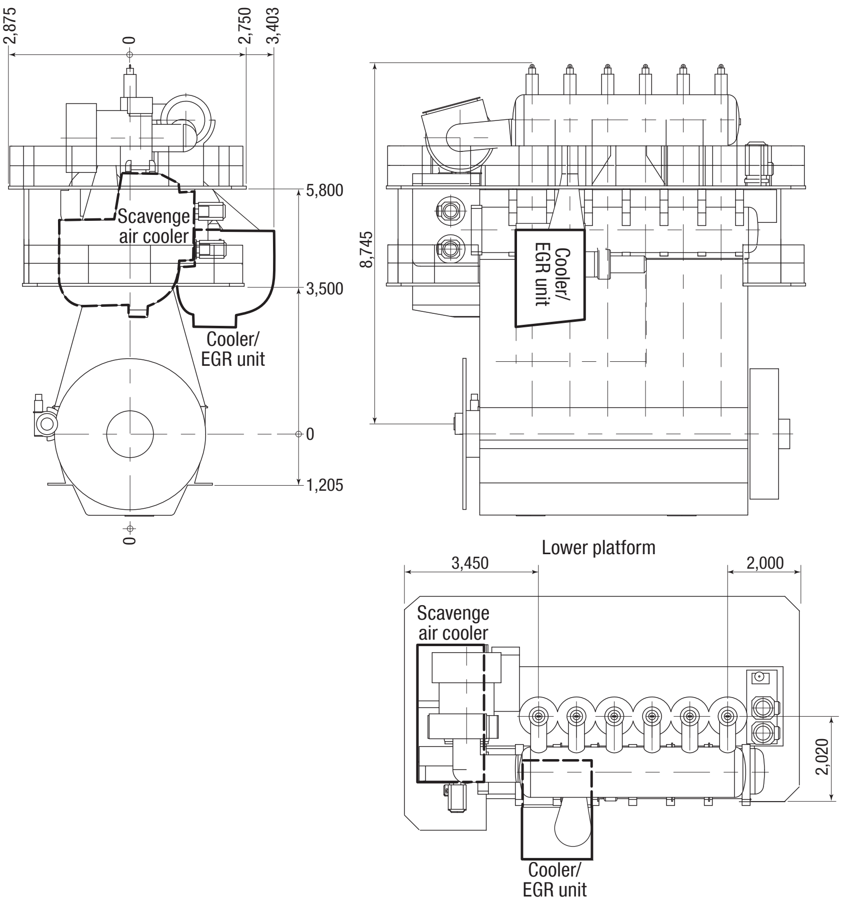

Fig. 1.12: EGR engine with one aft-mounted turbocharger and side-mounted EGR unit, example from 6G50ME-B9

TC cut-out matching

The outline of an EGR system with TC cut-out matching is shown in Fig. 1.13.

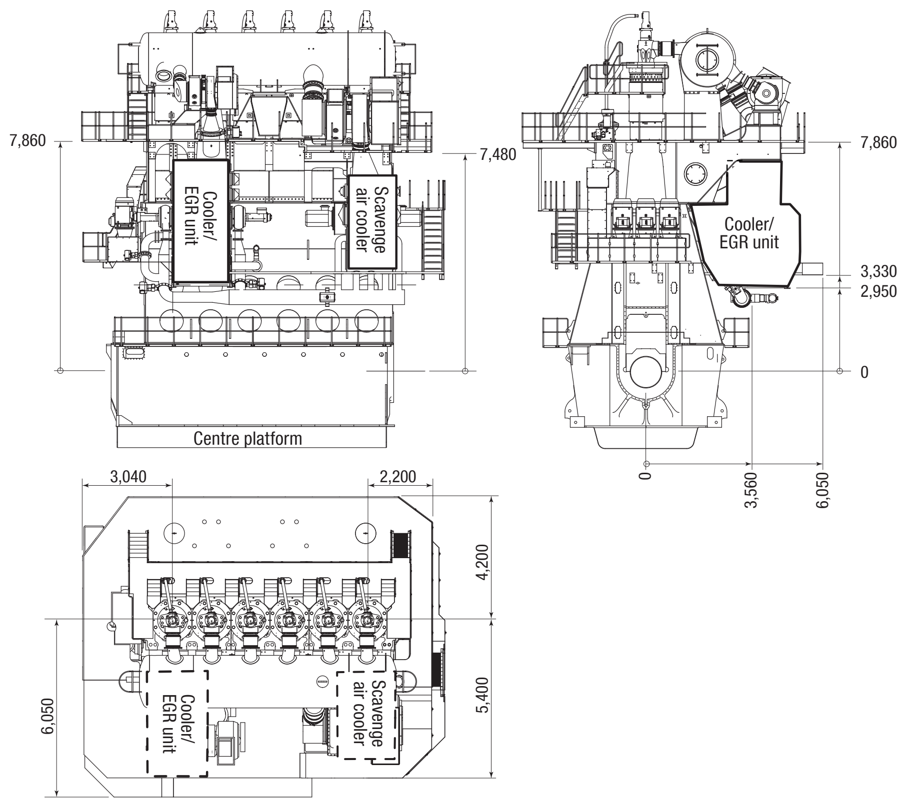

Fig. 1.13: Outline of a 6S80ME-C9.2 Tier III engine with one basic T/C, one cut-out T/C and one EGR unit, example from 6S80ME-C9 - EGR

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1.2.6 Water Treatment System (WTS)

WTS principle

To prevent sulphur and particles from damaging the engine, cleaning of the re-circulated exhaust gas is required. The cleaning is done by a scrubbing process in the EGR unit using recirculated freshwater (FW).

In order to maintain the ability to clean the exhaust gas, a water treatment system (WTS) is needed. The system must ensure the removal of accumulated particles and neutralisation of sulphuric acid in the scrubber water and ensure the delivery of water at a sufficient supply rate and pressure to the EGR unit. In addition, the WTS must also handle the surplus of water accumulated in the system from the combustion process. If discharged overboard, the water quality must meet the international requirements for scrubber water outlet as stated in *2009 Guidelines for Exhaust Gas Cleaning Systems*, MEPC 184 (59).

A water treatment system approved for the EGR Tier III process is available from Alfa Laval. The system consists of a collecting tank unit (CTU) placed below the EGR unit, which receives and redirects the untreated scrubber water, and a water treatment unit (WTU) that cleans the scrubber water and delivers it to the EGR unit.

To supply the WTS with additive for sulphur neutralisation and to store the sludge generated from the cleaning process, an NaOH tank and an EGR sludge tank are required. The principle of the water treatment system including tanks is illustrated in Fig. 1.14.

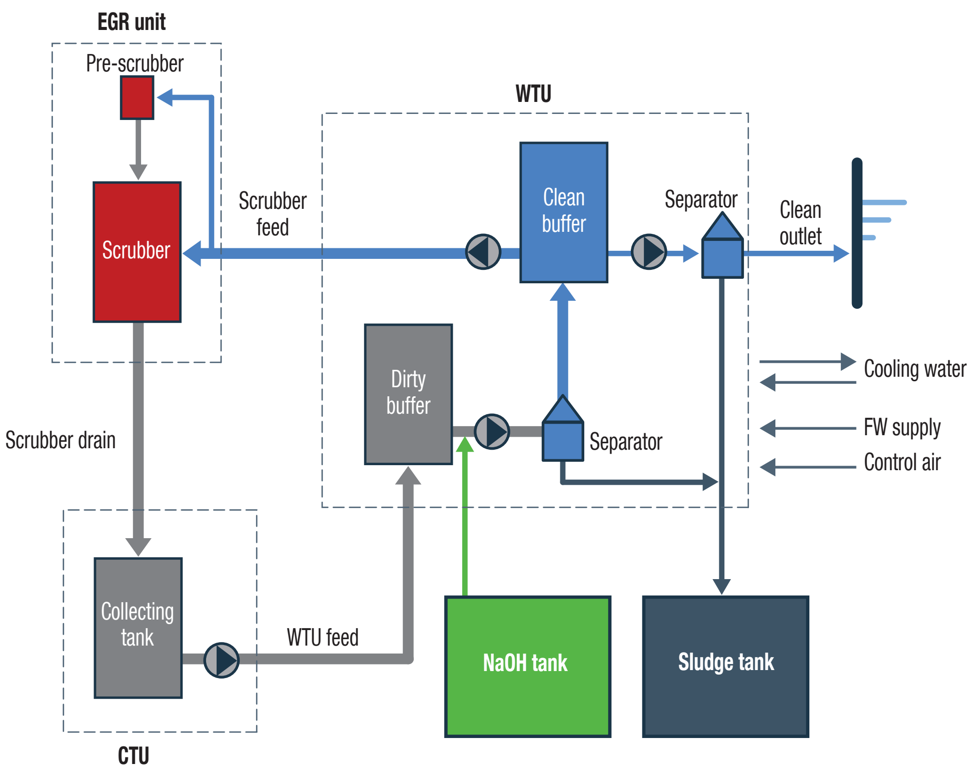


Fig. 1.14: Diagram showing WTS units, tanks and pipe connections

WTS layout

The principle used in the WTS is independent of the different EGR layouts of the engine. However, the capacity must be designed to handle the maximum scrubber water flow required for the EGR process, which depends on the engine size. Having this requirement in mind, the layouts of the CTU and the WTU described below are basically not affected, but the size and number of the elements in the system must be designed for the actual engine size. The NaOH tank, the sludge tank and the pipe connections are yard deliveries described in the installation chapter.

Collecting Tank Unit

The CTU, which includes a buffer tank and a feed pump, must be placed at a level sufficiently below the EGR unit to enable correct drainage of the scrubber. The purpose of the unit is to allow a freedom in the arrangement of the WTU. Other solutions for redirecting the scrubber water to the WTU are possible. The CTU is shown in Fig 1.15.

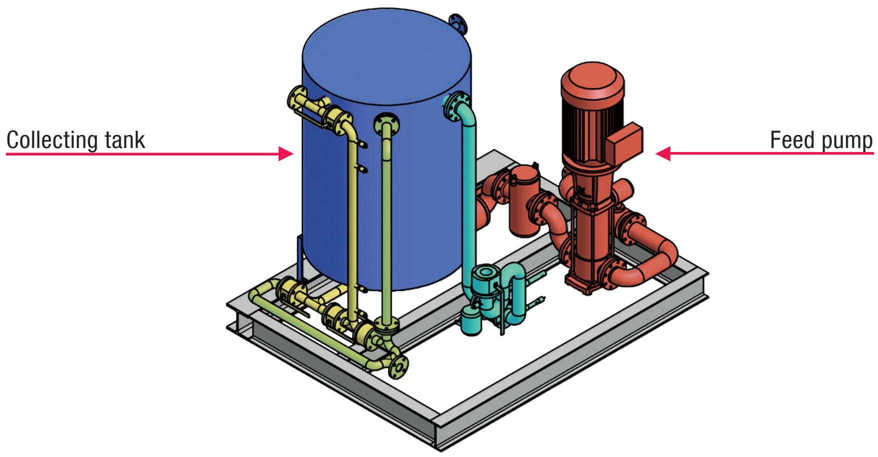


Fig. 1.15: Collecting tank unit by Alfa Laval

Water Treatmentnit

The WTU shown in Fig. 1.16 has two functions. The primary function, which cleans and neutralises the scrubber water, includes a dirty buffer tank, one or more full flow separators, a clean buffer tank and a scrubber water pump. The secondary function, which enables discharge of the excess water generated in the EGR system from the combustion process while meeting the IMO discharge criteria, includes a pump, a bleed-off separator and a water quality test unit. The WTU furthermore includes one or more NaOH pumps and an electric control cabinet.

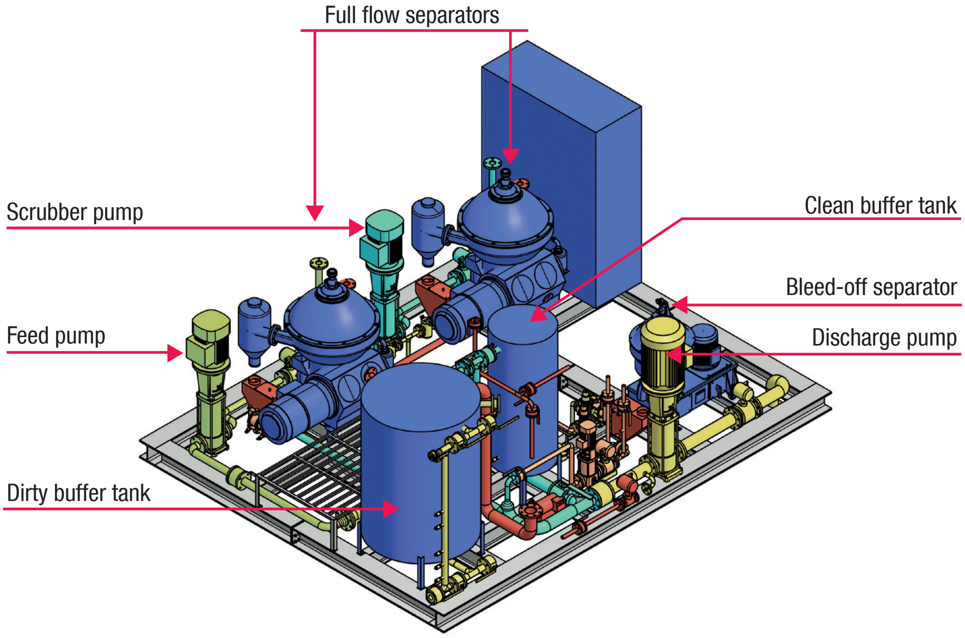
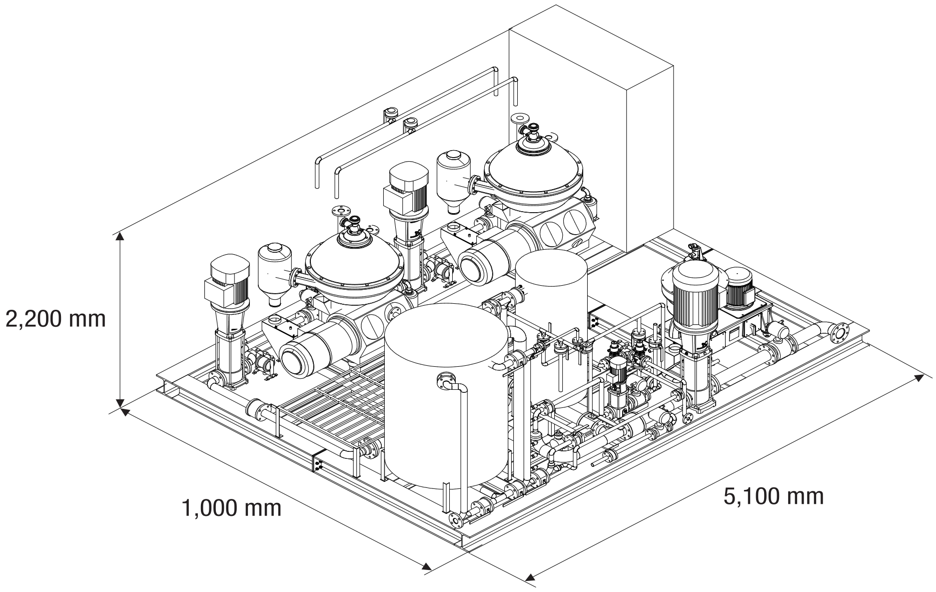


Fig. 1.16: Water treatment unit with two full flow separators, by Alfa Laval

WTS outline

An example of outlines for the collecting tank unit and a water treatment unit for a 25 MW MAN B&W marine engine is shown in Fig. 1.17. Additional space above the separators might be needed for maintenance.



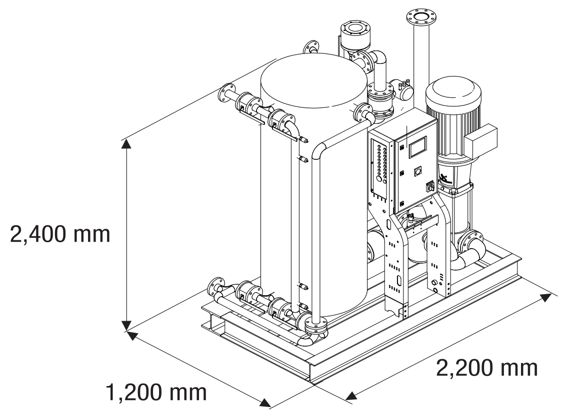


Fig. 1.17: Outline of an Alfa Laval CTU and WTU for a 25 MW MAN B&W marine engine

1.2.8 Control system

The system set-up consists of three separate systems integrated through simple signal interfaces as briefly described below.

EGR control system

The EGR control system consists of a number of controllers arranged in one cabinet for mounting on the engine, an uninterruptible power supply (UPS) cabinet for hull-side mounting and a main operating panel with touch screen to be installed in the engine control room (ECR). The EGR control system is the master control for the EGR system and controls the remaining sub-systems.

EGR blower control

The EGR blower control consists of one control cabinet and, depending on the number of blowers, one or two frequency converter cabinets, all for hull-side mounting. The control cabinet comprises a local operating panel displaying system status, alarms and parameters. Optionally, a similar control panel can be installed in the engine control room.

The control cabinet monitors and controls the blowers and adjusts the exhaust gas flow according to input from the EGR control system. Each blower is controlled via a frequency converter. Special requirements apply for the power cabling between the frequency converter and the blower to ensure compliance with EMC regulations.

WTS control

The WTS control system controls all pumps, separators and valves in the WTS. The main control is found on the WTU frame, from which the CTU is interfaced and controlled. The WTS control has a local control panel as well as an ECR control panel with touch screen for easy operation.

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1.2.9 Installation

Engine room arrangement

An arrangement of the water treatment system in the engine room is shown in Fig. 1.18. The collecting tank unit (CTU) is placed on the tank top sufficiently below the EGR unit to enable correct drainage of the EGR scrubber. The system allows flexibility to arrange the water treatment unit (WTU) in the engine room, but a position nearby the EGR unit is beneficial. The NaOH storage tank is located close to the WTU where the additive is used. The sludge tank could be placed in the double bottom either as a separate sludge tank or as part of a dirty bilge tank, see also Fig. 1.14 in the chapter regarding WTS.

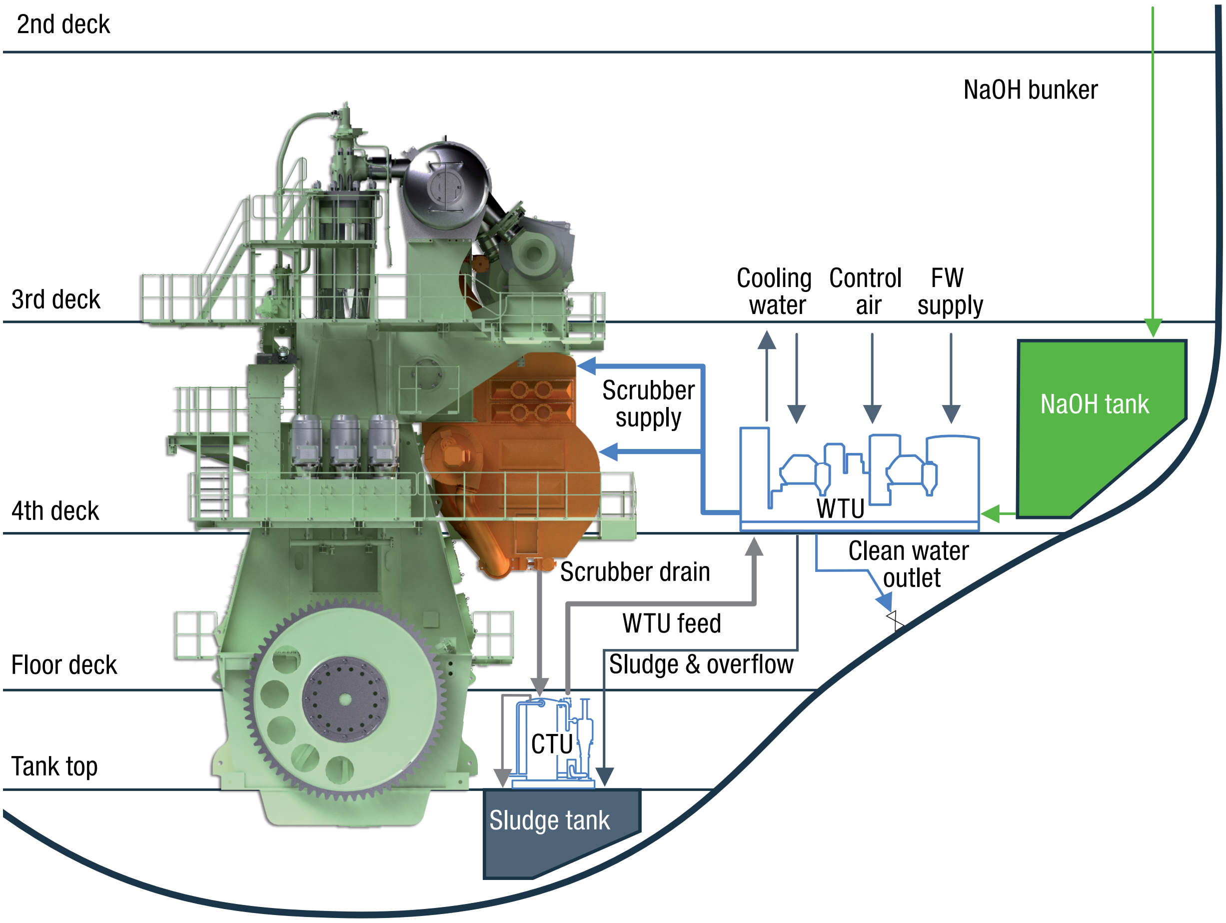

Fig. 1.18: Example of engine room arrangement

Pipes and flanges

As the scrubber water flow relates to the engine power, the pipe dimensions in the WTS will vary depending on the engine size. Table 1.19 shows examples of system pipes, which are to be supplied by the yard.

Pipe	Connection	Ø inch	P R. bar	Media	Material
Scrubber supply	WTU to EGR unit	4.0	0-10	Scrubber water	Stainless, 316 L
Scrubber drain	EGR unit to CTU	4.5	0.5-5	Scrubber water	Stainless, 316 L
WTU feed	CTU to WTU	4.0	0-5	Scrubber water	Stainless, 316 L
Clean water outlet	WTU to over-board valve	1.0	0-5	Scrubber water	Mild steel, galv.
Sludge and overflow	WTU to sludge tank	1.5	0-5	Sludge	Stainless, 316 L
CTU overflow	CTU to sludge tank	2.0	0-5	Sludge	Stainless, 316 L
NaOH supply	NaOH tank to WTU	1.0	0-5	NaOH fluid	Stainless, 316 L
NaOH bunker	NaOH tank to bunker	2.5	0-5	NaOH fluid	Stainless, 316 L
Freshwater supply	FW system to WTU	1.0	2-8	Water	Mild steel, galv.
WTU cooling water in	Cooling system to WTU	1.0	0.1-3	Water	Mild steel, galv.
WTU cooling water out	WTU to cooling system	1.0	0.1-3	Fluid	Mild steel, galv.
Operating water	FW system to CTU	0.5	2-8	Water	Mild steel, galv.
Sludge discharge	Sludge tank to discharge	2.5	0-5	Fluid	Mild steel, galv.
Collecting tank venting	CTU to upper deck	2.0	0	Air	Mild steel, galv.
Buffer tank venting	WTU to upper deck	2.0	0	Air/Gas	Stainless, 316 L
NaOH tank venting	NaOH tank to deck	1.0	0	Air/Gas	Stainless, 316 L
Sludge tank venting	Sludge tank to deck	1.5	0	Air/gas	Mild steel, galv.
WTU control air	Control air to WTU	-	2-8	Gas	Stainless, 316 L
CTU control air	Control air to CTU	-	0-10	Air/Gas	Stainless, 316 L

Table 1.19: Pipes in the EGR arrangement with dimensions relative to a 25 MW engine.

NaOH tank

The NaOH tank should be suitable for the media, normally a 50% NaOH solution. Such a solution will start to crystallise below 12 °C, and the tank should therefore keep a minimum temperature of 16 °C. Accordingly, the tank should therefore be installed in a room with a controlled temperature or be insulated and fitted with means for heating. Furthermore, the temperature in the tank should be kept below 45 °C to prevent other negative impacts from the solution. The material of the tank must be suitable for the NaOH solution, such as stainless steel, coated steel, polymer or other materials fulfilling the relevant requirements. [5]

When estimating the capacity of the NaOH tank, the ECA sailing time, the sailing pattern, the fuel sulphur content, the NaOH solution and the planned bunker period must be considered. Furthermore, the capacity could include additional volume to receive a full standard bunker volume when refilling.

An example of dimensioning the NaOH tank is found in the tables in section 1.2.11 Calculation of EGR data.

5 *See also The Chlorine Institute, Pamflet 94 regarding storage and piping*

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Sludge tank

The sludge outlet from the WTU is an aqueous solution of combustion particles, sulphur compounds and other material separated from the scrubber water. The pH value would normally vary between 6 and 9. The water content in the sludge is more than 90%, which makes it easy to discharge by a pump. The sludge tank could be a separate tank or part of another tank, i.e. the dirty bilge tank, which holds similar sludge from the engine room to be discharged to reception facilities. The tank could be of coated steel taking the variation of pH value into consideration.

When estimating the capacity of the sludge tank, it is important to take into account the ECA sailing time, the sailing pattern, the fuel sulphur content, the water content and the planned discharged period. Furthermore, additional volume should be included to allow for overflow from the CTU and WTU.

An example of dimensioning the tank is found in the tables in section 1.2.11 Calculation of EGR data.

1.2.10 Consumptions and capacities

The following estimated performance and consumption data are based on ISO conditions, except where otherwise stated. [6]

Specific fuel oil consumption

The EGR concept affects the performance data of the engine. The exhaust gas amount is reduced due to the recirculation of exhaust gas, and the specific fuel oil consumption (SFOC) therefore normally increases due to the changes in the combustion process.

In Tier III mode, the SFOC increases to a maximum of 4.0 g/kWh at 100% MCR compared to the standard Tier II engine. The change of SFOC is shown in Fig. 1.20.

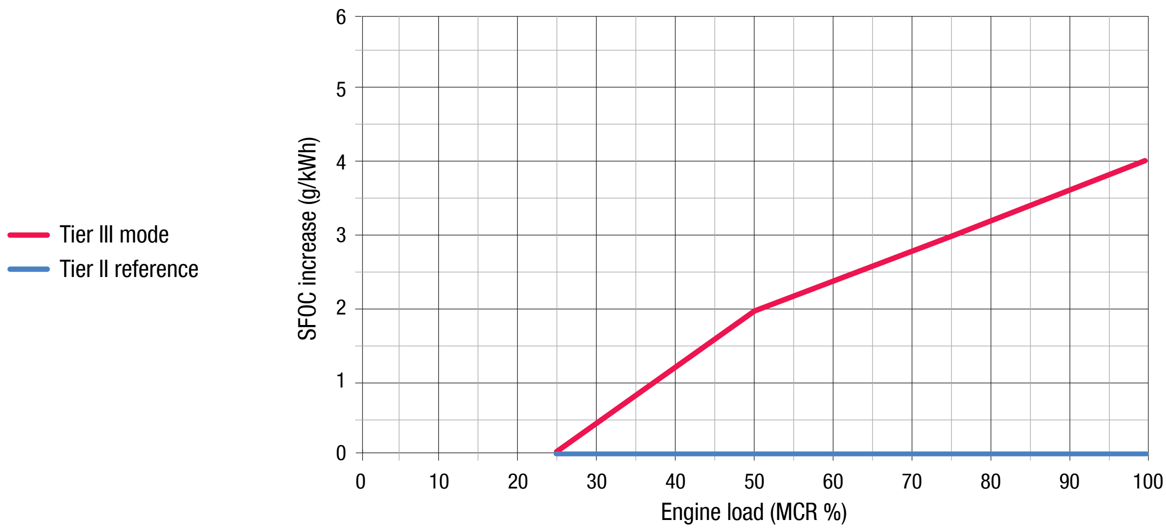

Fig. 1.20: SFOC increase relative to a standard Tier II engine

6 *All data presented are approximate values and subject to change without further notice*

Power consumption

The additional electrical power required for the EGR system is related to the EGR unit and the WTS, although other consumers also have some minor influence on the power required, i.e. cooling water pumps to the EGR cooler.

Water treatment system (WTS)

The electrical power required for the WTS relates to the scrubber water flow, which is dependent on the specified engine power. The main consumers are the full flow separators, but also the scrubber water pumps are significant consumers. The power needed for the WTS depending on the engine load is shown in Fig. 20.

EGR blower

The electrical power required for the EGR unit relates to the EGR blower, which raises the pressure of exhaust gas for recirculation. The power is relative to the engine size, the engine load and the EGR rate. The power needed for the blower depending on the engine load is shown in Fig. 1.21.

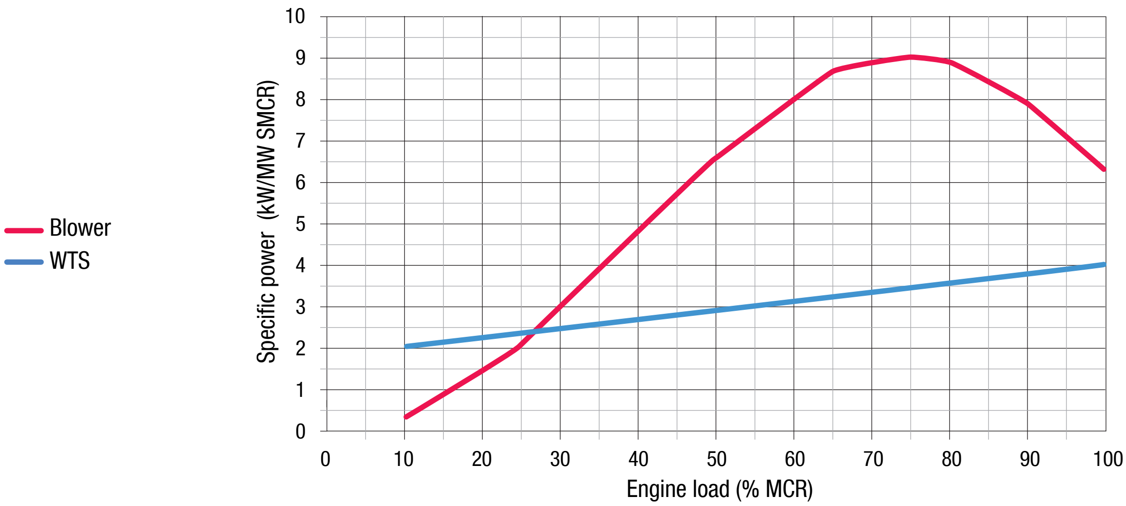

Fig. 1.21: Power consumption for WTS and EGR blower

NaOH consumption

The additive applied to neutralise the accumulated sulphur in the scrubber water is normally a 50% NaOH solution. The amount of NaOH applied depends on the engine size, the SFOC, the engine load, the EGR ratio and, finally, on the sulphur content in the fuel.

Fig. 1.22 shows the estimated NaOH consumption, using a 50% NaOH solution, relative to the engine load, engine size and sulphur content. The figure represents a standard SFOC for EGR Tier III engines. It should be kept in mind that any use of high-sulphur fuel (>0.1% S) would normally also require a SO_x scrubber system due to the ECA rules. The NaOH consumption using fuel with 0.1% sulphur is shown in Fig. 1.23.

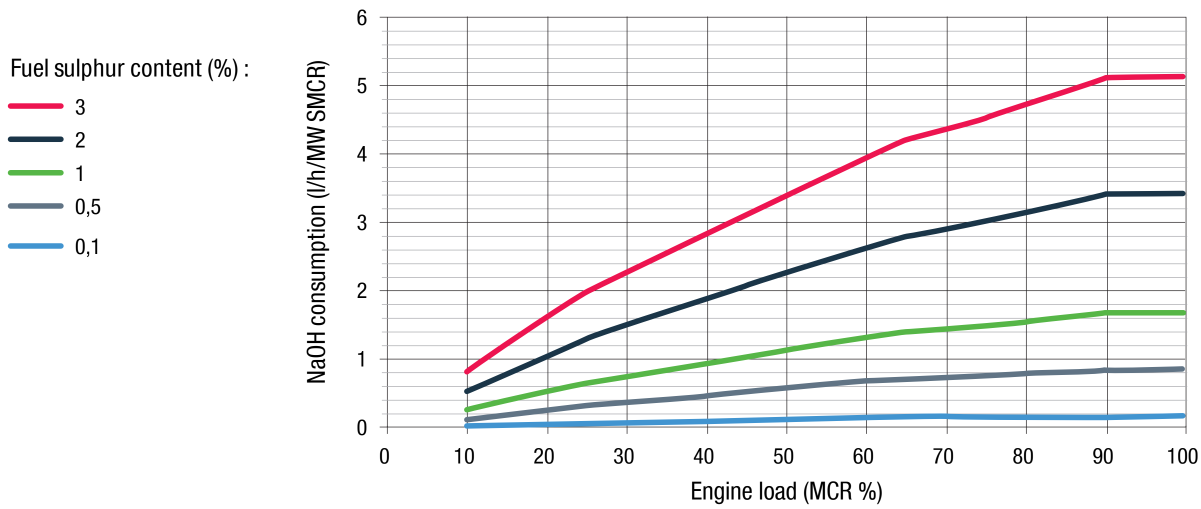

Fig. 1.22: NaOH consumption in Tier III mode – 50% NaOH solution

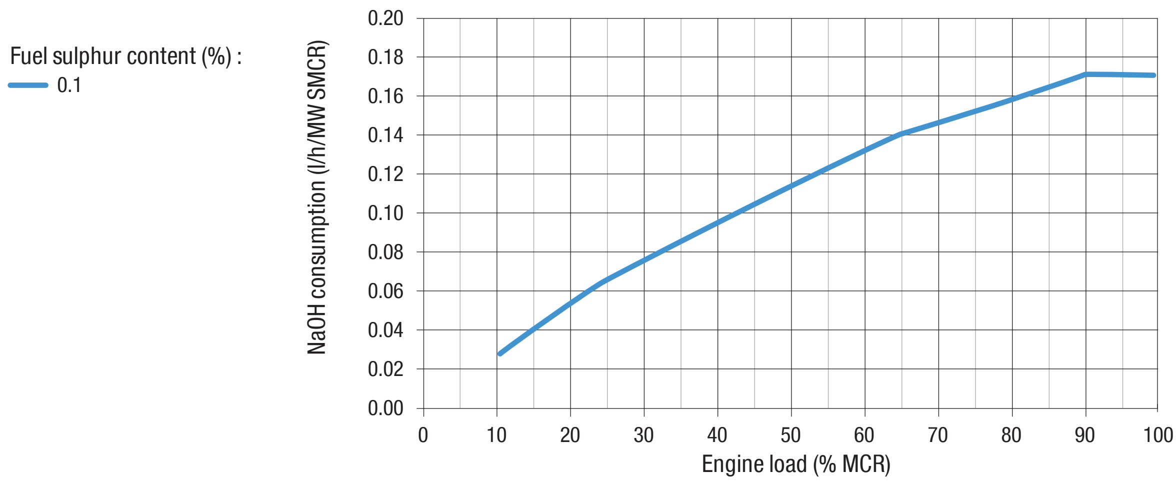

Fig.1.23: NaOH consumption in Tier III mode using ECA fuel (0.1% sulphur) and 50% NaOH solution

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Sludge production

The sludge accumulated in the scrubber water when cleaning the exhaust gas is removed by the separators in the WTS. The same parameters, which have an influence on the NaOH consumption, also influence the sludge amount. In addition, however, some sludge will be produced independently of the sulphur content.

In addition to the above-mentioned relations, the water content in the sludge will have a significant impact on the sludge production. A solution of 93% water and 7% sludge is chosen as the standard; a lower fraction of water will increase the viscosity and might give problems in handling the sludge, and a higher value will rapidly increase the volume needed to store the sludge. As an example, an increase from 93% to 95% water content will increase the volume by 40%.

In Fig. 1.24 the estimated sludge production relative to the engine load and engine size is shown. The water content in the sludge is set at 93%, which is assumed to be an appropriate ratio. As for the NaOH consumption it should be kept in mind that any use of high sulphur fuel (>0.1% S) would normally also require a SO_x scrubber system due to the ECA rules.

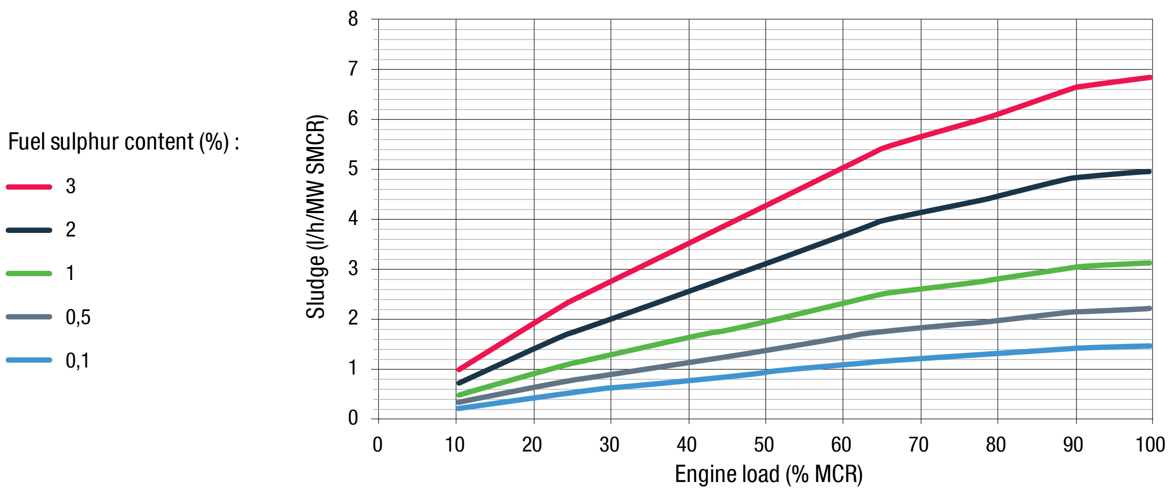


Fig. 1.24: Sludge production in Tier III mode – water content 93%

Freshwater consumption

Due to the neutralisation of sulphur, the WTS process will accumulate salt in the scrubber water, which could lead to deposits in the EGR unit. Furthermore, the density of the scrubber water will increase with increased salinity, and this will have a negative impact on the effect of the WTU separators. However, as the EGR system generates water due to the condensation of exhaust gas in the EGR unit, the salt will be diluted and discharged together with the surplus of water through the WTS discharge system. In most cases there will be sufficient water to keep the concentration of salt below the required limit. In certain conditions with a high fuel sulphur content (above 2%) and a low relative humidity (RH), there will be a need for additional freshwater at low loads. However, this situation would normally also require a SO_x scrubber system due to the ECA rules, and the freshwater requirements would be significantly influenced by this system.

In addition to diluting the salt in the scrubber water, freshwater is also used as process water in the separator process. The water is used for the discharge of sludge, and the solution of water and sludge will end in the sludge tank.

Although various parameters will influence the required amount, the freshwater consumption could be calculated from the sludge volume including a surplus of 20%, i.e. sludge × 120%.

EGR cooling water capacity

The capacity of cooling water for the EGR Tier III engine is increased due to the need for cooling the recirculated exhaust gas, which has a significantly higher temperature than the scavenge air it is replacing. The cooling water amount for scavenge air cooling is increased by about 45% compared to the standard Tier II engine when sailing in Tier III mode.

Lube oil capacity

The lubricating oil flow is only slightly increased on an EGR Tier III engine. The lubricating oil flow for the EGR blowers, which are the only additional consumers, will be around 0.3 m^3/h/MW SMCR with a minimum of 3.6 m^3/h.

Compressed air capacity

Compressed air is needed for sealing of the EGR blower and for control purposes throughout the EGR system. The required sealing air for the EGR blower will be around 2.5 kg/h/MW SMCR with a minimum of 30 kg/h.

1.2.11 Calculation of EGR data

An example of EGR data for a 27 MW MAN B&W marine engine is calculated below for a standard sailing pattern using the information of consumption and capacities given in the diagrams. The calculation assumes that no SO_x abatement techniques are available, which implies that the fuel sulphur content is not to exceed 0.1% as required for SO_x ECA. A higher sulphur content will significantly increase the NaOH and sludge amount.

Assumptions:

Engine	6S80ME-9.2	
Power, SMCR	27060 kW	
RPM	78.0	
EGR system	TC cut-out matching	
ECA Fuel Sulphur content	0.1% S	
NaOH solution	50%	
NaOH tank margin	33%	
Sludge tank margin	33%	
NaOH bunker frequency	2 times/year	
Sludge discharge frequency	12 times/year	
ECA sailing time	2,000 h/year	
ECA sailing profile	25% MCR	15% time
ECA sailing profile	50% MCR	15% time
ECA sailing profile	75% MCR	50% time
ECA sailing profile	100% MCR	20% time

Step 1

The first step is to find the specific data on SFOC penalty, electric power consumption, NaOH consumption and sludge production as specified in 1.2.10 'Consumptions and capacities'.

- The SFOC penalties at the specified loads are stated in g/kWh in Fig. 1.19.
- The electric power consumption values for the WTS and the EGR blower are stated at the specified loads in Fig. 1.20. The power data in the figure is related to the engine maximum specified power, SMCR, and is stated in kW per MW SMCR.
- The NaOH consumptions values at the specified loads are stated in Fig. 1.22. The NaOH data is related to the engine maximum specified power, SMCR, and to the sulphur content of the fuel, in this case 0.1% S. The data is stated in litres per MW SMCR.
- The amount of sludge produced is stated in Fig. 1.23. The sludge data is related to the engine maximum specified power, SMCR, and to the sulphur content of the fuel, in this case 0.1% S. The data is stated in litres per MW SMCR.
- Finally, the specific freshwater consumption is found by using the relation stated in the previous chapter: FW volume = 120% x sludge volume, calculated in litres per MW SMCR.
- The data stated under Step 1 is listed in Table 1.25.

Step 2

The second step is to calculate the absolute consumption at each load point for the specific engine. The SFOC penalty is found by multiplying the data found in Step 1 by the engine power delivered at the requested loads. The absolute consumption values of power, NaOH, FW and production of sludge are found by multiplying the data found in Step 1 by the specified engine power, SMCR = 27,060 kW. The calculated data is listed in Table 1.25.

Step 3

The total consumption in an ECA area, i.e. when the SCR system is operating, will depend on the sailing profile and the sailing time in the ECA. When multiplying the absolute consumption values with the profile values, the average consumption for one hour is found when adding these values. The yearly consumption is found when the sailing time in ECAs is known – in this case 2,000 h/year. The result is shown in Table 1.25.

Step 4

The tank capacity can be calculated when the bunker frequency of reducing agent is known. A margin should be included to compensate for variations in the sailing profile and sailing hours and for leaving space to receive a full lot size at delivery. The result of the calculation, assuming a bunker frequency of 6 times per year and a tank margin of 33%, is shown in Table 1.25.

Step 1 – Specific ECA consumptions – as specified in the consumption data

Engine load, % MCR	25%	50%	75%	100%	
Delta SFOC Tier III	0.0	2.0	3.0	4.0	g/kWh
Power, WTS	2.4	2.9	3.5	4.0	kW/MW SMCR
Power, EGR blower	2.0	6.5	9.0	6.2	kW/MW SMCR
NaOH	0.07	0.11	0.15	0.17	l/h/MW SMCR
Sludge	0.5	0.9	1.3	1.4	l/h/MW SMCR
EGR freshwater	0.6	1.1	1.6	1.7	l/h/MW SMCR

Step 2 – Absolute ECA consumptions – according to specified engine

Engine load, % MCR	25%	50%	75%	100%	
Delta SFOC Tier III	0.0	27.1	60.9	108.2	kg/h
Power WTS	64.9	78.5	94.7	108.2	kWh/h
Power EGR blower	54.1	175.9	243.5	167.8	kWh/h
NaOH	1.9	3.0	4.1	4.6	l/h
Sludge	13.8	25.4	36.0	38.2	l/h
EGR freshwater	16.6	30.5	43.3	45.9	l/h

Step 3 – Total ECA consumptions – according to specified load profile and ECA sailing time

Engine load, % MCR	25%	50%	75%	100%	Total		Total	
ECA load profile Time	15%	15%	50%	20%	per hour		per year	
Additional fuel	0.0	4.1	30.4	21.6	56.1	kg/h	112.3	ton/year
Power WTS	9.7	11.8	47.4	21.6	90.5	kWh/h	181.0	MWh/year
Power EGR blower	8.1	26.4	121.8	33.6	189.8	kWh/h	379.7	MWh/year
NaOH	0.3	0.4	2.0	0.9	3.7	l/h	7.4	m^3/year
Sludge	2.10	3.8	18.0	7.6	31.5	l/h	63.1	m^3/year
EGR freshwater	2.5	4.6	21.6	9.2	37.9	l/h	75.7	m^3/year

Step 4 – Tank capacities

Item	Bunker/Year	Volume	Margin	Tank
NaOH tank	2	3.7m^3	33%	4.9 m^3
Sludge tank	12	5.2 m^3	33%	7.0 m^3

Table 1.25: ECA consumptions, tank capacities

1.3 SCR principle – Selective Catalytic Reduction

Selective Catalytic Reduction (SCR) is an exhaust gas treatment method by which the NO_x generated in a marine diesel engine can be reduced to a level in compliance with the NO_x Tier III requirements.

The NO_x reduction is obtained by a catalytic process in an SCR reactor installed in the exhaust line after the combustion process. In the SCR reactor, the NO_x is reduced catalytically to nitrogen and water by adding ammonia as a reducing agent. The catalyst in the reactor consits of blocks with a large number of channels, providing a large surface area, in which the catalytic process takes place, see Fig. 1.26.

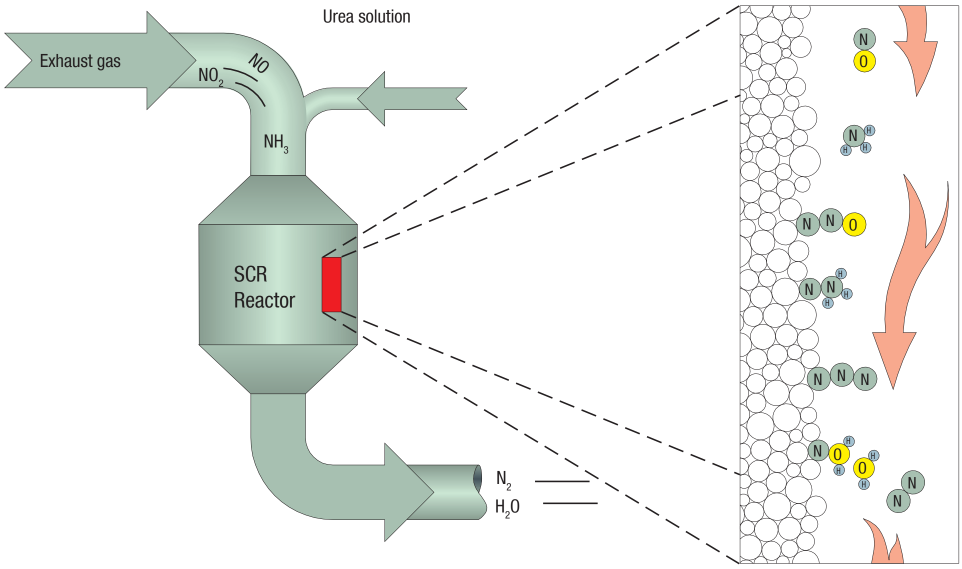


Fig. 1.26: The SCR system

NO_x is reduced according to the following overall reaction scheme:

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

$2\ NO + 2\ NO_2 + 4\ NH_3 \rightarrow 4\ N_2 + 6\ H_2O$

$2\ NO_2 + 4\ NH_3 + O_2 \rightarrow 3\ N_2 + 6\ H_2O$

For reasons of safety, the ammonia is normally added to the system in the form of aqueous urea. This decomposes to ammonia and carbon dioxide when it is injected into the vaporiser:

$(NH_2)_2CO_{(aq)} \rightarrow (NH_2)_2CO_{(s)} + x\ H_2O_{(g)}$

$(NH_2)_2CO_{(s)} \rightarrow NH_{3(g)} + HNCO_{(g)}$

$HNCO_{(g)} + H_2O_{(g)} \rightarrow NH_{3(g)} + CO_{2(g)}$

1.3.2 SCR system

SCR operation

An essential parameter of the SCR process is the inlet gas temperature. A lower temperature limit is dictated by the sulphur content in the fuel and the subsequent formation of sulphurous acid in the gas. At temperatures below approximately 320 °C, the sulphuric acid is neutralised by ammonia.[7] This forms a sticky product, ammonium bisulphate (NH_4HSO_4), which may accumulate in the SCR elements. However, if the exhaust gas temperatures are kept above 350 °C, this reaction can be suppressed. When the sulphur content in the fuel is below 0.1%, a temperature of approximately 310 °C would be sufficient. At low exhaust gas pressures, the required temperatures will be lower.

The minimum temperatures required to avoid the formation of ammonia bisulphate are shown in Fig. 1.27, which shows the relation between the fuel sulphur content and the exhaust gas pressure. Fig. 1.27 shows a high pressure curve (4.0 bara) and a low pressure curve (1.5 bara).

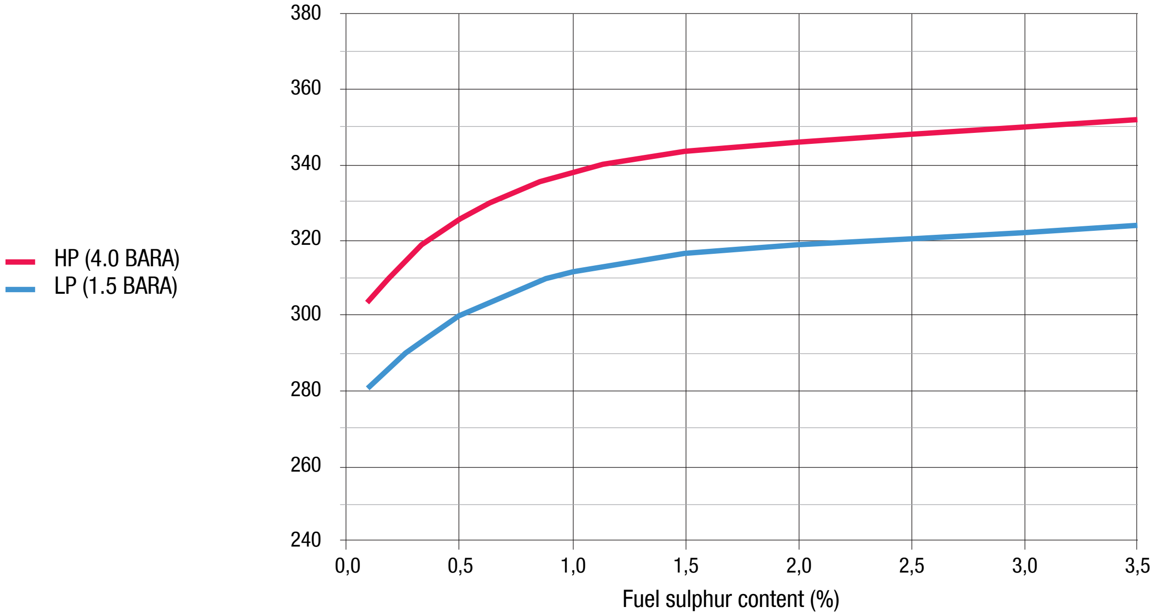


Fig. 1.27: Required temperatures for SCR related to sulphur content and exhaust gas pressure

On the other hand, the temperature must not be too high as this will result in an increased SO_3 formation in the catalyst. SO_3 subsequently reacts with water creating sulphuric acid, which appears as an undesired white aerosol plume. Another undesired reaction which also limits the upper temperature for SCR operation is the oxidation of NH_3 as the exhaust gas temperature approaches 500 °C, i.e. more NH_3 is needed. Additionally, the catalyst material starts to sinter at temperatures above 500-550 °C. The temperature depends on the material and results in a loss of catalytic activity.

In other words, to ensure a robust SCR operation it is crucial to maintain exhaust gas temperatures within a certain temperature window.

7 *The temparature limit may vary depending on the catalyst type.*

SCR process

The SCR process, illustrated in Fig. 1.28, takes place in the SCR line, which consists of two major components: the combined vaporiser/mixer unit and the SCR reactor. In the vaporiser, the catalytic process is prepared by injecting the reducing agent which will vaporise and mix with the exhaust gas. The prepared gas is led to the SCR reactor where the NO_x reduction takes place.

Due to the demand for a relatively high temperature of the SCR process, the SCR line on two stroke marine diesel engines is placed on the high pressure side, i.e. before the turbocharger. Depending on the engine load, the exhaust gas temperature on this side is 50-175 °C higher than on the low pressure side.

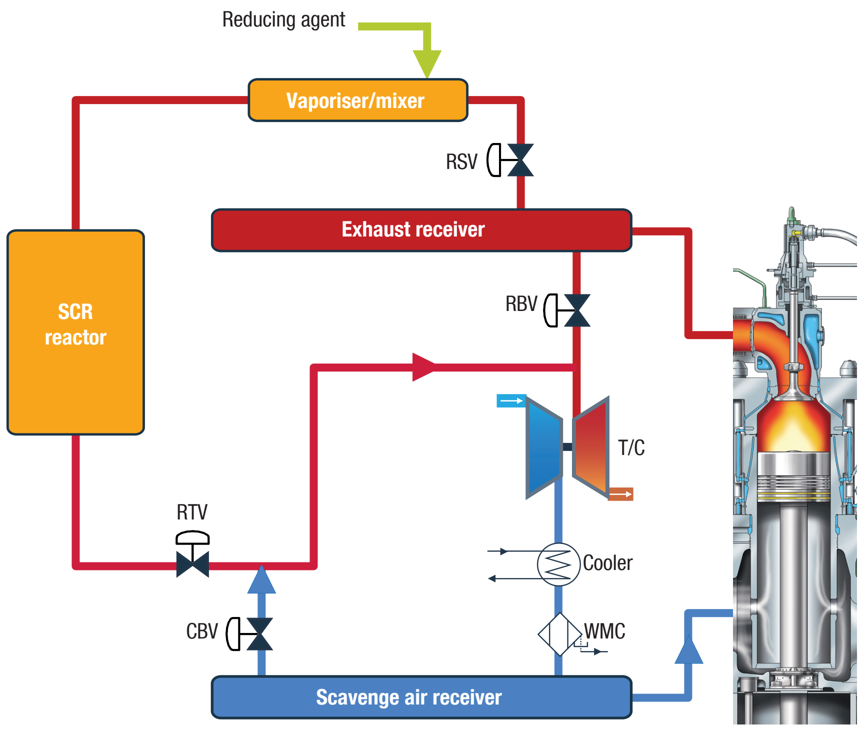


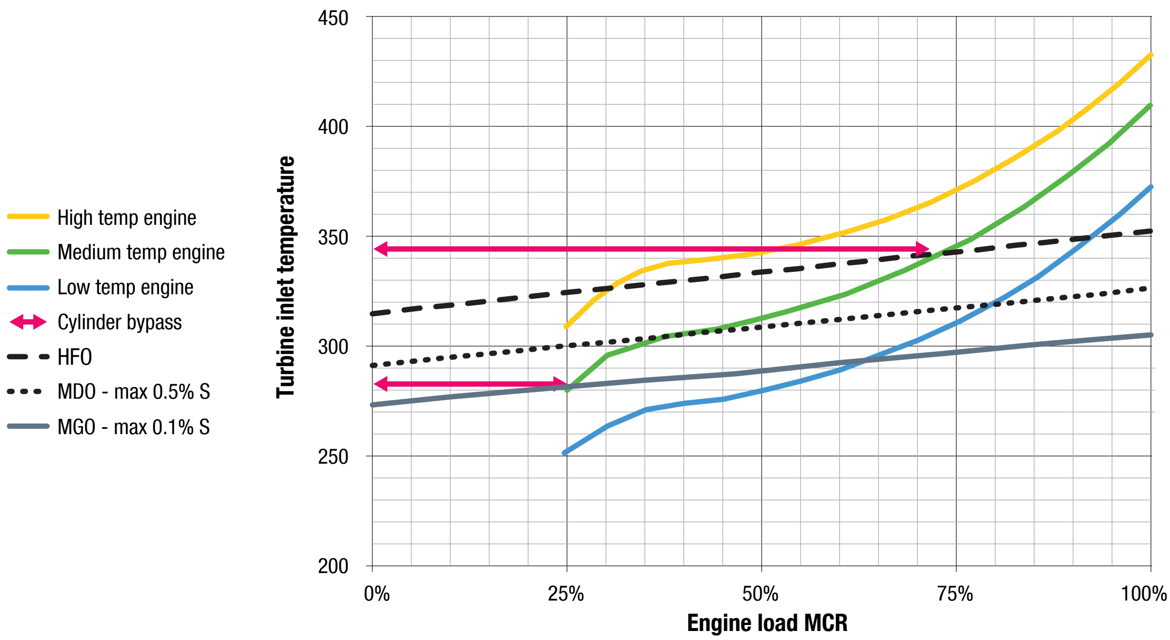
Fig. 1.28: SCR system diagram

When operating in Tier II mode, the SCR system is cut off by the reactor sealing valve (RSV) and the reactor throttle valve (RTV). The reactor bypass valve (RBV), is open and exhaust gas passes directly to the turbocharger. When operating in Tier III mode the SCR system will be engaged. The SCR line is opened by the valves, RSV and RTV, while the valve RBV will be closed.

Even though the reactor is placed before the turbine, the exhaust gas temperature will normally still be too low at low loads. To increase the temperature, a cylinder bypass from the scavenge air receiver to the turbine inlet is installed. The bypass is controlled by the cylinder bypass valve, CBV. When opening the bypass, the mass of air through the cylinders will be reduced without loosing the scavenge air pressure and, accordingly, the exhaust gas temperature will increase. This system makes it possible to keep the temperatures above the required level. However, the cylinder bypass will increase the SFOC depending on the required temperature increase.

Fig. 1.29 illustrates the load range in which the cylinder bypass must be engaged to keep a sufficient temperature for the SCR process. It illustrates the dependence on the fuel sulphur content as the bypass must be open in a wider range when using high-sulphur fuel. Furthermore, as the temperature curve of the turbine inlet depends on the type and layout of the engine, the required range will be wider on an engine with a relative low turbine inlet temperature compared to one with a higher temperature.

Fig. 1.29: Turbine inlet temperatures and required SCR temperatures



At low loads, below 10-15% MCR depending on the engine and sulphur content, the urea injection will be suspended in order to prevent deposits in the SCR system caused by insufficient temperatures.

As the SCR reactor and the vaporiser has a significant heat capacity due to the size and mass of the components, the temperature of the exhaust gas after the SCR reactor will only increase slowly during SCR start-up and during engine acceleration. In these situations, the turbocharger cannot deliver sufficient charge air and the auxiliary blowers must be used to assist the process. For this reason, the capacity of the auxiliary blowers must be increased.

In some cases it may also be required to install a turbine bypass. This is the case if the heat transfer from the SCR system to the exhaust gas is too high during a decrease in the engine load. In such cases the energy in the exhaust gas will lead to too high a scavenge air pressure compared to the current engine load. This could be avoided by a turbine bypass.

1.3.3 SCR layout

Although the SCR system is closely related to the engine, the SCR line – including the vaporiser/mixer, the SCR reactor and the connection pipes – is not part of the engine delivery. The SCR layout will therefore vary depending on the SCR supplier. The system, however, must be based on specifications from MAN Diesel & Turbo.

The size of the SCR components is determined by the gas flow and is dependent on the specified engine power, but other factors influence the size too. Among these factors are:

- the specified lifetime of the catalyst elements – if an increased lifetime of the catalyst elements is required, the volume of catalyst and accordingly the size of the reactor will increase
- the choice of reducing agent – if ammonia is chosen as reducing agent, the process time for vaporising is eliminated and only a small mixer is needed.

An example of an SCR arrangement supplied by Hitachi Zosen Corporation is shown in Fig. 1.30. It illustrates the relative size and location of the SCR components and the position of the control valves. The arrangement could be made differently depending on engine room restrictions.

The systems needed for the supply of a reducing agent and for keeping the catalyst elements free of soot is described in a separate chapter concerning auxiliary systems.

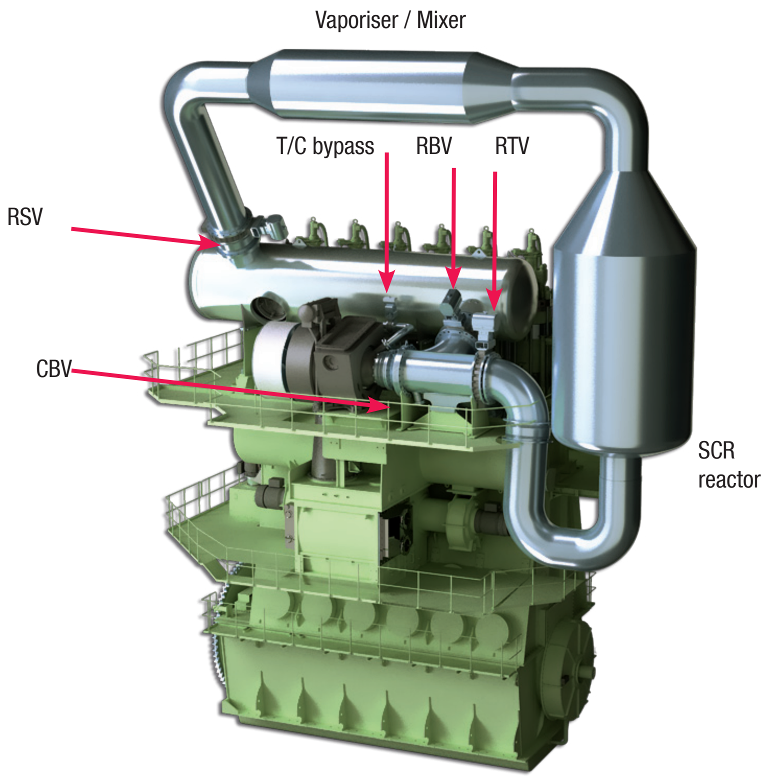


Fig. 1.30: Example of an SCR system supplied by Hitachi Zosen

1.3.4 Outline

An example of an MAN B&W Tier III engine with SCR, excluding the auxiliary system, is shown in Fig. 1.31. The arrangement of the vaporiser and the SCR reactor including the connection pipes will depend on the engine room arrangement.

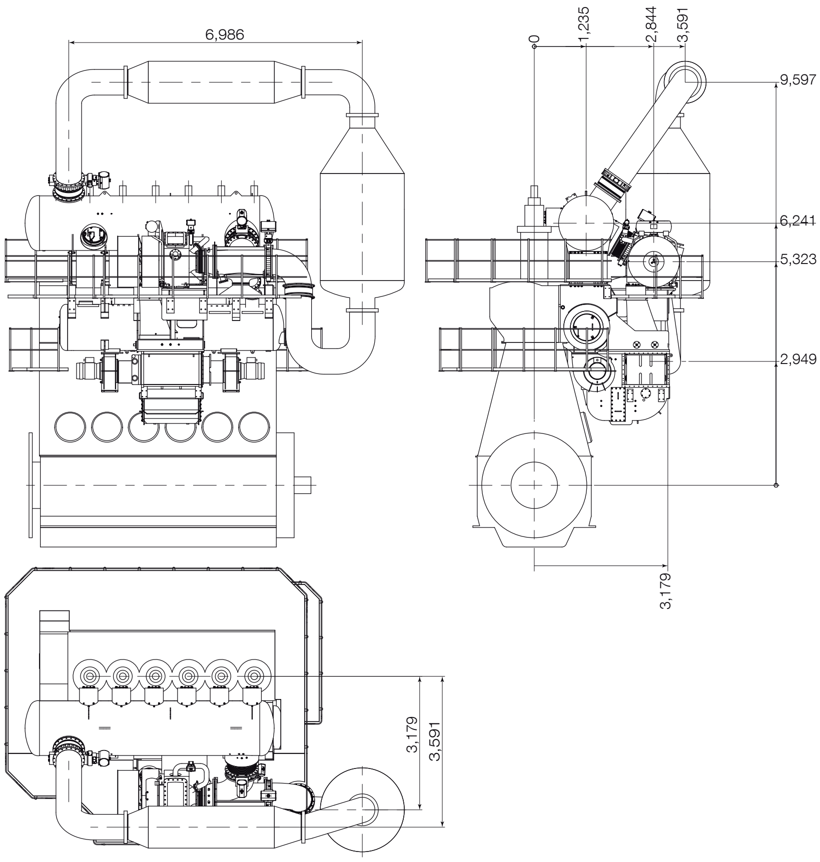


Fig. 1.31: SCR installation on an 8 MW engine (6S46ME-B) with Hitachi Zosen SCR system

1.3.5 SCR auxiliary systems

Supply system of reducing agent

The reducing agent used for the SCR process is either anhydrous ammonia (NH_3), aqueous ammonia (25% NH_3), aqueous urea (32.5% or a 40% solution).

As anhydrous ammonia (NH_3) is classified as a toxic and dangerous substance, it is convenient for marine purposes to use urea, which has no significant hazards. In addition, the urea supply system is less complex than the supply system for anhydrous ammonia, but the consumption and storage volume of urea is larger. In addition, urea requires a more complex vaporising and mixing process which influences the layout of the SCR system. Aqueous ammonia (25% NH_3), although corrosive and dangerous for the environment, could with some precautions be handled like urea. Independent of the selected reducing agent, the injection is performed in combination with compressed air.

It is essential that both the injection and the mixing of the reducing agent are performed effectively. Any unused ammonia, defined as the ammonia slip, is likely to react with the exhaust gas to become ammonium bisulphate (NH_4HSO_4) when the temperature decreases, and involves the risk of deposits in the exhaust gas system, e.g. in the exhaust gas boiler.

- Urea

  An example of a urea supply system is shown in Fig. 1.31a. From the storage tank, urea is pumped to the vaporiser/mixer by a urea pump in the supply unit. The supply unit also has a wash water tank and a pump for purging the urea injection nozzles. A control unit controls the injection of urea and compressed air into the vaporiser. When the SCR process is shut down, the urea injection nozzles are purged with wash water to prevent clogging of the nozzles. As an alternative, urea could be stored as solids and mixed on board

- Ammonia (aqueous solution)

  Ammonia supplied as an aqueous solution of NH_3 (25% solution) is classified as corrosive and dangerous for the environment. Although special precautions must be taken, the supply system is nearly the same as for urea. The consumption and storage volume for this solution is largely the same as for urea.

- Ammonia (NH_3 anhydrous)

  Ammonia supplied as anhydrous NH_3 is classified as a toxic substance and dangerous for the environment. In a normal ambient condition, NH_3 is a gas, and for this reason it will be kept pressurised as a liquid in the ammonia tank. The storage tank and the part of the supply system that includes an evaporator must be situated in a separate room away from the machinery room and the accommodation. The supply line for the injection must be a double-wall pipe, ventilated to open air. As NH_3 is used directly in the reduction process, the time required for vaporising is eliminated, and the vaporiser/mixer can be replaced by a smaller mixer. An example of the ammonia supply system is shown in Fig. 1.31b.

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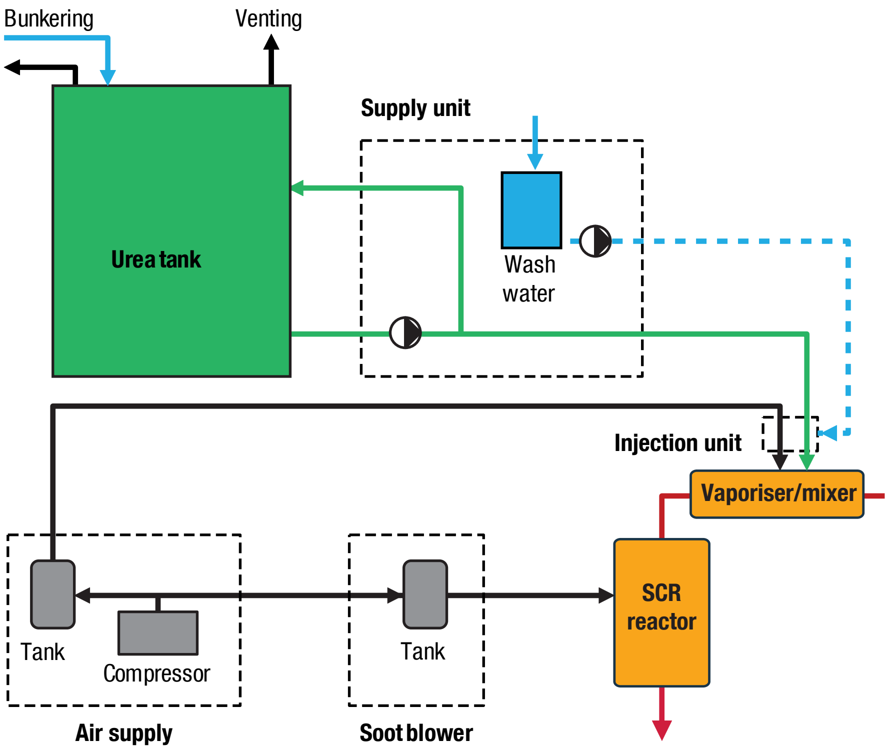

Fig. 1.31a: Example of urea supply system and soot blower system

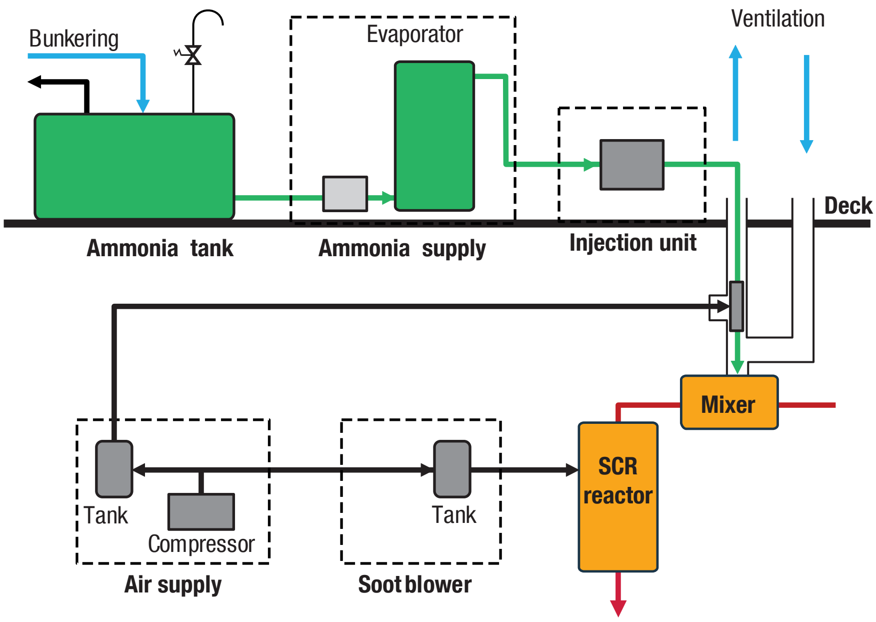

Fig. 1.31b: Example of supply system for anhydrous ammonia

Soot blower system

To prevent contamination of the reactor elements, a soot blower system – shown in Figs. 1.31a and 1.31b – is installed. The soot blower process is performed periodically during the SCR process and the soot is led out with the exhaust gas after being blown loose from the elements inside the reactor.

SCR heating

The SCR reactor and the vaporiser have significant heat capacities due to the size and mass of the components. The system should normally be engaged in due time before entering a NO_x ECA to obtain the right operating temperature of the SCR reactor and vaporiser. However, when in harbour, i.e. at engine standstill, the temperature will slowly decrease and means to keep the temperature at the required level or to heat up the system must be available. To meet this demand, the system needs to be equipped with heat tracing or other appropriate means.

1.3.6 SCR control system

The SCR system is controlled by the SCR valve control system (SCR-VCS) and the SCR dosing control system (SCR-DCS). The essential input parameters for the control systems are the temperatures (Tscr_in and Tturb_in), the engine load and the NOx amount either from a map and/or from one or more sensors (N1) shown in the diagram in Fig. 1.32.

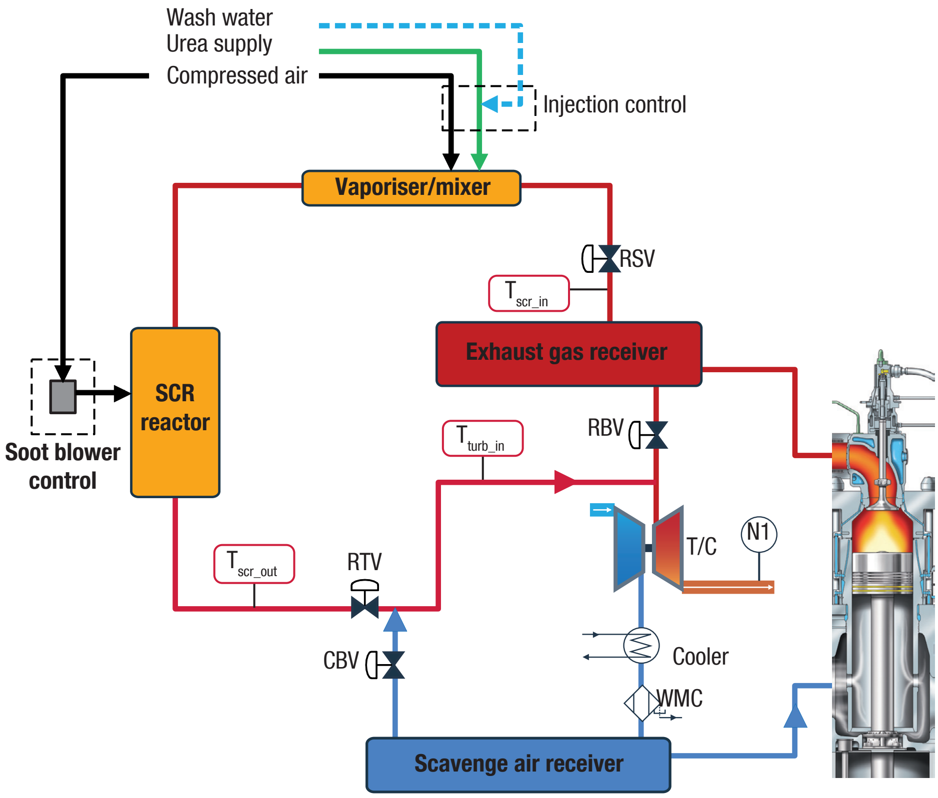

Fig. 1.32: Control parameters of SCR system

SCR-valve control system (SCR-VCS)

The SCR-VCS controls the temperatures in the SCR system. This is done by the RBV, RTV, RSV and CBV valves, based on input from the temperature sensor T_{scr_in} at the exhaust gas receiver and the sensor T_{turb_in} before the turbine inlet. The purpose is to obtain an acceptable exhaust gas temperature in the SCR reactor while ensuring an acceptable turbocharger performance. When the required temperatures in the reactor and at the turbine inlet are reached, the valves RSV and RTV are opened and RBV is closed. The CBV is used to increase the exhaust gas temperature at low load to extend the load range for the SCR operation. At rapid acceleration, the RBV is opened to ensure turbocharger and engine performance. The SCR-VCS is developed and delivered by the engine builder.

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SCR dosing control system (SCR-DCS)

The SCR-DCS controls the injection of the reducing agent. To prevent slip of the reducing agent and the risk of deposits in the reactor, injection is not permitted when the exhaust gas temperature in the SCR system is out of range. The output value of the T_{scr_in} and T_{scr_out} temperature sensors, is used for this purpose. The control of the injected volume is based on engine load and NO_x amount from either a NO_x map that is also based on engine load and/or NO_x measurements. Furthermore, the SCR-DCS controls the soot blowing of the catalyst elements. The SCR-DCS is developed and delivered by the SCR supplier.

1.3.7 Installation

Engine room arrangement

An arrangement of an SCR installation using urea as the reducing agent is shown in Fig. 1.33. The arrangement includes a compressor unit supplying compressed air to the injection process and to the soot blower system. The compressor can be part of the general supply of compressed air for the engine room or, alternatively, be dedicated to the SCR system.

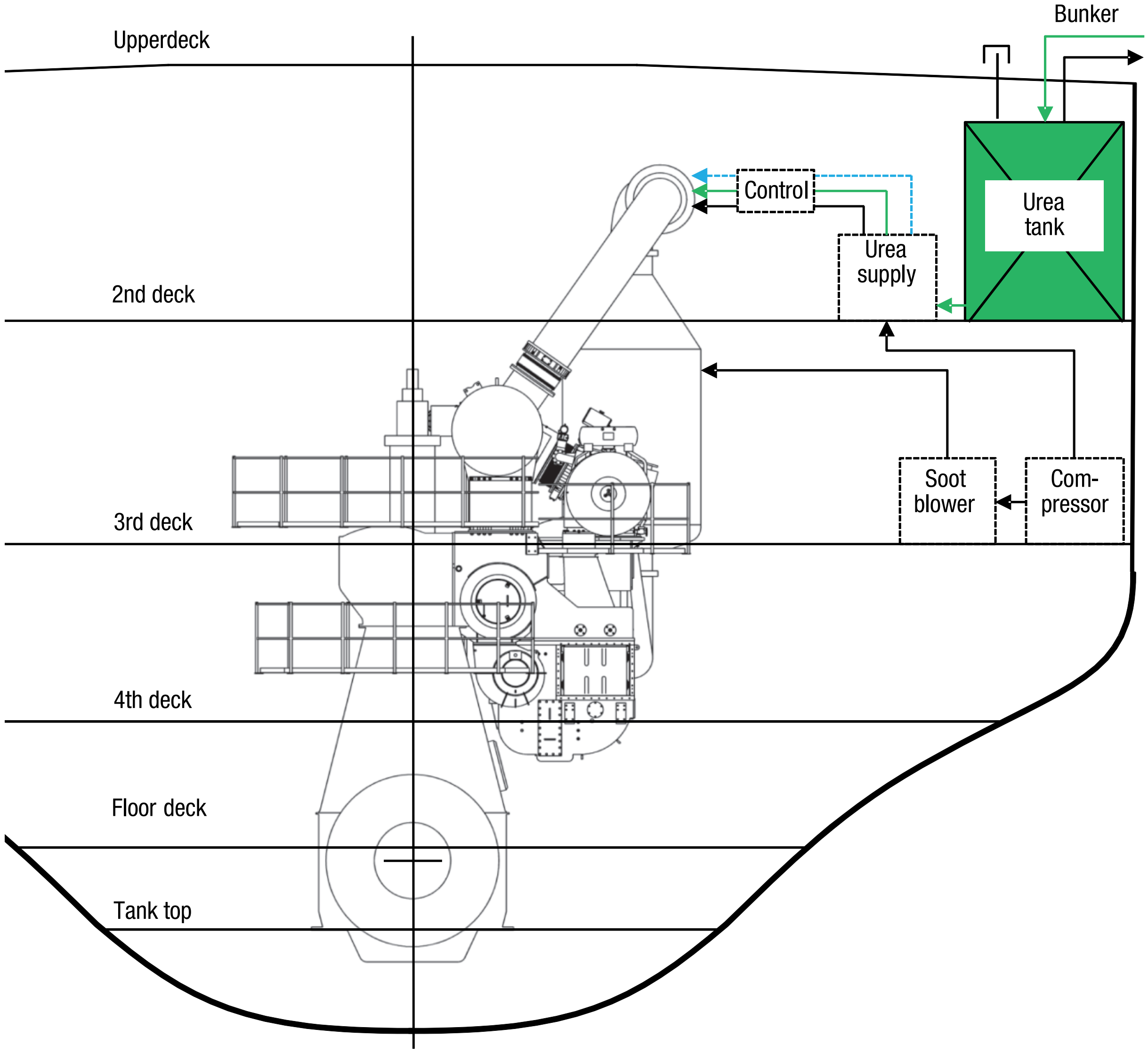

Fig. 1.33: Example of an SCR arrangement in the engine room

Storage tank arrangement

Due to different hazards and different specific consumptions, the arrangement and volume of the storage tank for the reducing agent will depend on the actual choice of reducing agent.

The required volume of the tank depends on the consumption of the specific reducing agent, the estimated ECA sailing time, the sailing pattern, and the planned bunker period. Furthermore, the lot size of the reducing agent when bunkering should be taken into consideration. An example of dimensioning the storage tank is found in the following chapter, 'Consumption and capacities'.

- Urea tank

  The urea tank could be an independent tank suitable for the solution or an integrated tank properly coated. The tank must be ventilated to open air, and the bunkering system should include a vapour return pipe to the bunker delivery.

- Ammonia tank (aqueous solution)

  With aqueous ammonia as the reducing agent, it must be stored in an independent tank suitable for the solution. The tank and the supply system should be placed in a separate room ventilated to open air and the supply pipes in the engine room must be laid in ventilated ducts or double-walled pipes. The bunkering system must include a vapour return pipe to the bunker delivery.

- Ammonia tank (NH_3 anhydrous)

  If anhydrous NH3 is the reducing agent, enhanced safety precautions must be taken. The tank must be pressurised, and it must be placed in a separate room ventilated to open air just like the supply system. The supply pipes in the engine room must be laid in ventilated ducts or double-wall pipes. The bunkering system is pressurised and must follow special design criteria.

1.3.8 Consumptions and capacities

The following estimated performance and consumption data are based on ISO conditions, except where otherwise stated.

Specific fuel oil consumption

The SCR concept affects the performance data of the engine. The main influence on the specific fuel oil consumption (SFOC) comes from the cylinder bypass. The SFOC penalty is mainly found at low loads and it is highly dependent on the specific engine and on the fuel sulphur content. The SFOC could also be affected by the increased pressure drop in the SCR line. However the addition of reducing agent, will generate additional heat and volume and, thereby, partly compensate the back pressure.

It should be kept in mind that any use of high-sulphur fuel (>0.1% S) would normally also require a SO_X scrubber system due to the ECA rules as explained in the introduction to this guide.

An estimate of the SFOC penalty is found in Table 1.34. The temperature level refers to the curves in Fig. 1.36. The turbine inlet temperature, however, is not available in MAN Diesel & Turbo's installation data application, CEAS [8], but could alternatively be related to the exhaust gas temperature, which is found by CEAS. The relation is set up in Table 1.35.

Fuel type	Temperature	MCR g/kWh			
		25%	50%	75%	100%
MGO ≤ 0.1% S	High	0,5	0,5	0,5	0,5
	Medium	1,0	0,5	0,5	0,5
	Low	2,0	1,0	0,5	0,5
MDO ≤ 0.5% S	High	0,5	0,5	0,5	0,5
	Medium	1,5	0,5	0,5	0,5
	Low	3,0	2,0	1,0	0,5
HFO > 0.5% S	High	1,5	0,5	0,5	0,5
	Medium	3,0	1,5	0,5	0,5
	Low	4,5	3,5	2,5	0,5

Table 1.34: SFOC penalty depending on turbine inlet temperature and fuel sulphur content – see Fig. 1.10

Exhaust gas temp – 100% MCR	Temperature level at turbine inlet
>255 °C	High
230 - 255 °C	Medium
<230 °C	Low

Table 1.35: Relation between turbine inlet temperature and exhaust gas temperature after TC at 100% MCR – ISO condition

8 *CEAS is found at http://www.mandieselturbo.com/ceas/index.html*

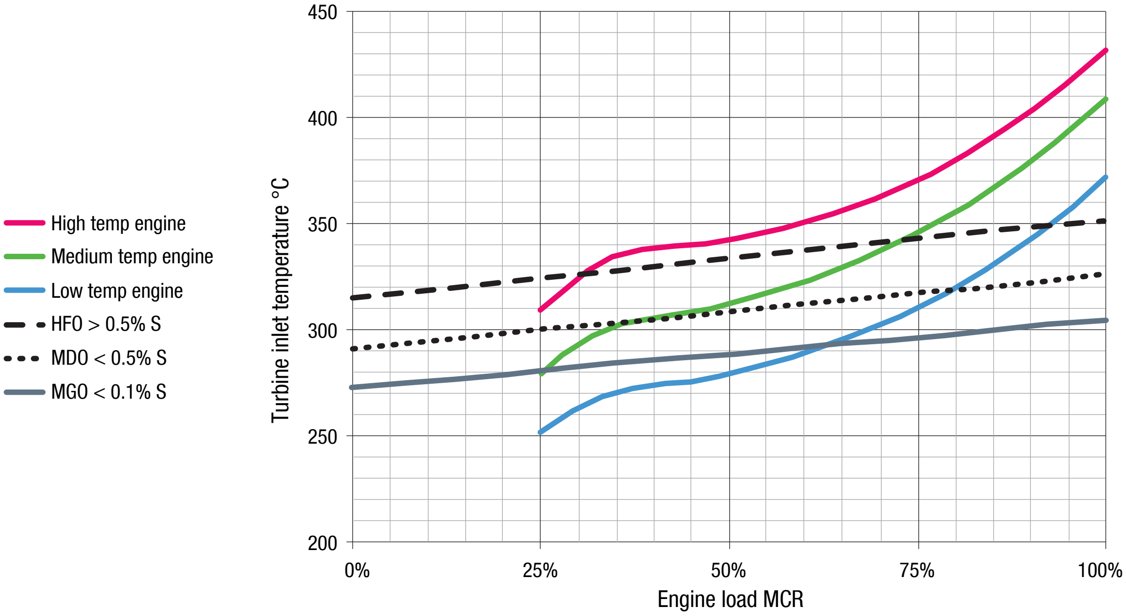

Fig. 1.36: Turbine inlet temperatures and required SCR temperatures

Electrical power consumption

The additional power required for the SCR system is related to the auxiliary systems for the SCR system. The main power consumers are the supply of reducing agent and the supply of compressed air.

The power consumption is estimated to 5 kW/MW SMCR

Consumption of reducing agent

The consumption of reducing agent depends on the agent type, the engine load and the NO_x reduction rate. The estimated specific consumption is shown in Table 1.37, in which the reduction rate is specified as the rate required to reduce the NO_x level from Tier II to Tier III (14.4 g/kWh to 3.4 g/kWh) using a constant NO_x level at all engine loads.

Reducing agent	g/kWh	l/kWh
Urea – 40%	17.9	0.0161
Urea – solid [8]	7.2	-
NH_3 – 24.5%	16.6	0.0184
NH_3 – anhydrous	4.1	0.0060

Table 1.37: Consumption of reducing agent

Catalyst consumption (replacement)

Depending on the load of the SCR reactor, the catalyst elements will slowly loose the ability to facilitate the NO_x reduction process. To keep the required efficiency of the reactor, the elements should be replaced periodically according to the catalyst supplier. Therefore, the catalyst elements are regarded as consumables and should be included in the running costs of the SCR system.

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9 *Additional urea handling system required. Water to be added on board*

The catalyst lifetime depends on the need for NO_x reduction. The engine load, the NO_x reduction rate and the time, during which the reactor is engaged, will directly influence the lifetime of the catalyst. The type and relative volume of the catalyst compared to the engine size will also influence the lifetime. The lifetime of the catalyst should be specified by the supplier.

Reactor size

The total volume required for the catalyst reactor elements is related to the exhaust gas mass flow and the engine size. In addition, the volume of the catalyst elements will depend on the catalyst type and, therefore, on the catalyst supplier. Finally, the required lifetime, the expected fuel sulphur content and the type of reducing agent will all have an influence on the catalyst volume. The actual reactor layout is designed according to the catalyst volume required (diameter, length, number of catalytic beds). The pressure drop of the reactor will be a function of the reactor design, i.e. the larger the diameter the lower the back pressure.

Vaporiser/mixer size

The size of the vaporiser/mixer depends on the reducing agent for the process. When using urea, the process of decomposing, vaporising and mixing will be long and the required volume is significant. Using a 25% ammonia solution will require less volume because decomposition is not needed. Anhydrous NH_3 requires neither evaporation nor decomposition – only the mixing process is needed, which will significantly reduce the size of the component. The mixing technology, which follows the supplier's standard, will have an influence on the SCR performance.

Compressed air capacity

The capacity of compressed air used for soot blowing and for the injection process relates to the reactor size, the type of reducing agent and the sulphur content in the fuel. As an alternative to a dedicated SCR compressor, it could be part of the general supply of compressed air for the engine room. The capacity of compressed air for the injection and soot blowing should be considered in the ship design process according to the supplier's standard.

SCR heating

The need for heating of the SCR components before leaving a port inside an ECA can be met by a number of different methods, but the capacity for the system chosen must be according to the SCR supplier's standard and be included in the capacity for ship.

1.3.9 Calculation of SCR Data

An example of SCR data for a 27 MW MAN B&W engine is calculated below for a specific sailing pattern using the information of consumption given in the previous chapter. The calculation assumes that no SO_x abatement techniques are available, which implies that the fuel sulphur content is not to exceed 0.1% as required for SO_x ECA.

Assumptions

Engine	6S80ME-9.4	
Power	27,060 kW MCR	
RPM	78.0	
ECA fuel S%	0.1% S	
Reducing agent	Urea 40% (NH_3 – anhydrous is shown as alternative)	
Tank margin	33%	
Bunker period	6 times/year	
ECA sailing time	2,000 h/year	
ECA sailing profile	25% MCR	15% time
ECA sailing profile	50% MCR	15% time
ECA sailing profile	75% MCR	50% time
ECA sailing profile	100% MCR	20% time

Step 1

The first step is to find the specific data on SFOC penalty, electric power and reducing agent as given in 1.3.8 'Consumptions and capacities'.

The SFOC penalty is found in Table 1.34. However, the temperature level is unknown and a CEAS report based on the engine data must be generated [10]. The exhaust gas data from the CEAS report, Fig. 1.38, shows an exhaust gas temperature of 240 °C at 100% load. Accordingly, as shown in Table 1.35, the SFOC penalty values of a medium temperature engine should be used. The SFOC penalty using the specified fuel of 0.1% S will be 1.0/0.5/0.5/0.5 g/kWh at 25%/50%/75%/100% MCR respectively.

Part Load Data at ISO Ambient Conditions

Load	Power	Speed	SFOC	Exh. gas amount	Exh. gas temp.
% of SMCR	kW	r/min	g/kWh	kg/h	°c
100.0	27,060	78.0	166.0	221,000	240.0
95.0	25,707	76.7	164.8	213,400	233.2
90.0	24,345	75.3	163,8	205,600	227.8

Figure 1.38: Details of CEAS report showing exhaust gas temperatures

According to 1.3.8, the electric power consumption will be 5 kW/MW SMCR and the consumption of urea (40%) will be 16.1 l/MWh. The consumption of the alternative reducing agent (NH_3 – anhydrous) will be 6.0 l/MWh.

The specific data found in Step 1 are listed in Table 1.39

10 *http://www.mandieselturbo.com/ceas/index.html*

Step 2

The absolute consumption at each load is found by multiplying the data found in Step 1 by the engine power delivered at the requested loads. Table 1.39b lists the absolute consumptions found from this calculation using the specified value of 27,060 kW at 100% MCR.

Step 3

The total consumption in an ECA area, i.e. when the SCR system is operating, depends on the sailing profile and the sailing time in the ECA. When multiplying the absolute consumptions with the profile values, the average consumption for one hour is found by adding these values. The yearly consumption is found when the sailing time in ECA-zones is known – in this case 2,000 h/year. The result is shown in Table 1.39c.

Step 4

The tank capacity can be calculated when the bunker frequency of reducing agent is known. A margin should be included to compensate for variations in the sailing profile and sailing hours as well as for leaving space to receive a full lot size at delivery. The result of the calculation assuming a bunker frequency of 6 times per year and a tank margin of 33% is shown in Table 1.39d.

Engine load, % MCR	25%	50%	75%	100%	
Delta SFOC, Tier III	1.0	0.5	0.5	0.5	g/kWh
Power supply	5.0	5.0	5.0	5.0	kW/MW SMCR
Urea supply	16.1	16.1	16.1	16.1	l/MWh
NH_3 supply (alt.)	6.0	6.0	6.0	6.0	l/MWh

Table 1.39a: Specific ECA consumption valves – as specified in the consumption data

Engine load, % MCR	25%	50%	75%	100%	
Delta SFOC, Tier III	6.8	6.8	10.1	13.5	kg/h
Power supply	135.3	135.3	135.3	135.3	kWh/h
Urea supply	108.9	217.8	326.7	435.7	l/h
NH_3 supply (alt.)	40.6	81.2	121.8	162.4	l/h

Table 1.39b: Absolute ECA consumption values – according to specified engine

Engine load, % MCR	25%	50%	75%	100%				
ECA load profile	15%	15%	50%	20%	Total per hour		Total per year	
Additional fuel	1.0	1.0	5.1	2.7	9.8	kg/h	19.6	ton/year
Power supply	20.3	20.3	67.7	27.1	135.3	kWh/h	270.6	MWh/year
Urea supply	16.3	32.7	163.4	87.1	299.5	l/h	599.0	m^3/year
NH_3 supply (alt.)	6.1	12.1	60.5	32.3	110.9	l/h	221.9	m^3/year

Table 1.39c: Total ECA consumption values – according to specified load profile and ECA sailing time [11]

Substance	Bunker/year	m^3	Margin	Tank	
Urea	6	99.8	33%	132.8	m^3
NH_3 (alternative)	6	37.0	33%	49.2	m^3

Table 1.39d: Tank capacity of reducing agent

11 In addition to the above consumption, the replacement of catalyst elements, which is also regarded as consumables, should be included in the evaluation

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