NATIONAL AND TECHNICAL UNIVERSITY OF ATHENS
SCHOOL OF MECHANICAL ENGINEERING

TITLE OF DIPLOMA DISSERTATION

EMISSION ABATEMENT TECHNIQUES FOR MARINE DIESEL ENGINES

Τεχνικές Μείωσης Ρύπων για Ναυτικούς Κινητήρες Diesel

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ABSTRACT

Environmental awareness has been grown radically over recent years.. For this reason, serious efforts have been made globally to curtail pollution in all its forms. This diploma dissertation reviews exhaust gas emissions of marine diesel engines, the corresponding maritime environmental legislation and the possible measures for controlling such emissions in marine installations. Pollutants emitted from marine diesel engines comprised of nitrogen oxides (NOx), sulfur oxides (SOx), soot, CO and unburned hydrocarbons whereas, emission standards have been issued only for NOx and SOx emissions. . International Maritime Organization (IMO) through MARPOL (International Convention for the Prevention of Pollution from Ships) 73/78 Convention adopted the new Annex VI in which limiting NO_x levels are defined by 17gr/Kwh when engine speed is 130rpm. The basis of the regulation is the fact that the average NO_x emissions of new ships must be some 30 per cent less than the emissions from ships in 1990. In special SOx Emission Control Areas (SECA) the sulfur content in fuel cannot exceed 15,000 ppm. Pollutant reduction technologies are divided into primary (i.e. internal) and secondary (i.e. external) methods. Primary measures focus on the reduction of in-cylinder pollutant formation whereas secondary measures deal with the abatement of the emissions in the exhaust gases. This study focus on the examination of NOx, SOx abatement techniques and also the technologies for reducing specific fuel consumption in marine diesel engines. These measures comprise of internal engine modifications (IEM), Exhaust Gas Recirculation (EGR), wet methods such as water emulsion, and SO_x abatements such as scrubbers. These techniques are reviewed and compared in an attempt to demonstrate the advantages and the challenges of each technique.

Keywords: marine diesel engines; pollutant emissions; environmental legislation; IMO; MARPOL; emission abatement techniques; NOx reduction techniques; SOx reduction techniques.

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PREFACE

This diploma dissertation is organized in eight chapters.

Chapter 1 gives an introduction about the typical marine and vessel characteristics and the fuel type which they are using.

Chapter 2 gives a reference about the green house gas emissions and the pollutants such as NOx SOx pm etc and the description of their formation.

Chapter 3 gives the climate policy such as ''the white paper and the green paper'', and information about international ship transportation and its effects on global climate change.

Chapter 4 refers to MARPOL arose out of the efforts of International Maritime Organization (IMO), a specialized agency to protect the environment from operational and accidental pollution from ships.

Chapter 5 refers to emissions produced at berth, sea or manoeuvring by auxiliary engines and main engines of marine ships.

Chapter 6 refers to emission reduction technologies especially NOx abatement techniques such as Internal engine Modifications, Exhaust Gas Recirculation etc, SOx abatement techniques (Scrubbers, low sulphur fuels), CO_2 abatement techniques (turbocharger+VTA control system) and other abatement techniques.

Chapter 7 refers to the Green ship of the future and its characteristics and describes how this green ship provides technology to obtain emissions reduction.

Chapter 8 gives the conclusions of this dissertation.

1 INTRODUCTION

This diploma dissertation describes the pollutants emitted from marine diesel engines and the methods used for the curtailment. A study of the exhaust gas emissions from a diesel engine represents a challenge to both the engine designers and to the developers of exhaust gas treatment equipment. It is also a valuable tool for reaching a deeper understanding of the engine combustion process. Such understanding has led to more serious treatment of environmental issues in the marine industry.

The increased emissions of NO_x to the atmosphere from combustion and contribution to smog formation is disturbing a very dedicate natural balance. Therefore, NO_x control is the number one emission control issue. Diesel engines emit about 1500 ppm of NO_x or about 17gr/Kwh while gas turbines emit around 200 ppm of NO_x. International Maritime Organization (IMO) through MARPOL (International Convention for the Prevention of Pollution from Ships) 73/78 Convention adopted the new Annex VI in which limiting NO_x levels are defined by 17gr/Kwh when engine speed is 130rpm. The basis of the regulation is the fact that the average NO_x emissions of new ships must be some 30 per cent less than the emissions from ships in 1990 [1]. Globally, the fuel consumed for national shipping activities (i.e., in-between domestic ports or on inland waterways) is relatively small compared to international shipping activities. However, for some countries national shipping activities may be larger consumers of fuel than international shipping. Table 1 provides a simple classification scheme and description of the navigation sub-sector. [2]

Table 1. Typical marine and inland vessel characteristics [2]

Vessel Classification	Usage Classification	Activity Class	Primary Fuel Type	Primary Engine Type	Auxiliary Power
Lake craft	Pleasure	Recreation, water sports	Gasoline (petrol)	2 or 4 stroke	Rare
River vessels	Pleasure or Commercial	Recreation, cargo or passenger	Gasoline (petrol) or diesel	4 stroke or diesel	Diesel engine
Coastal vessels	Commercial	Support, fishing	Diesel (200 – 3600HP)	Diesel	Diesel engine
Marine or ocean-going vessels	Commercial or Military	Cargo	Residual or distillate	Diesel	Diesel

2 PRODUCTION OF GREENHOUSE GASES AND POLLUTANT EMISSIONS FROM MARINE DIESEL ENGINES

2.1 General Information
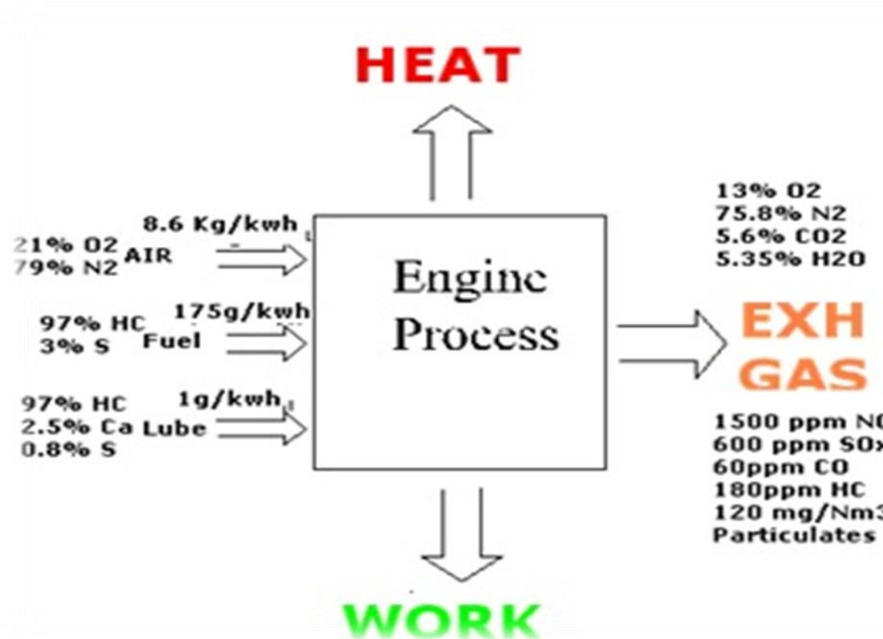
Figure 1. The pollutants in exhaust gases (% vol) of large diesel engines.[1]

Free nitrogen, N_2, and oxygen, O_2, comprise the major constituents of both the air intake and the exhaust emissions from a diesel engine. Nitrogen, forming 78%v/v of the intake air, basically does not react in the combustion process, although a very small proportion will react chemically with oxygen to form various oxides of nitrogen, jointly designated NO_x. Oxygen, originally forming 21%v/v of the intake air, will only be partially converted by the combustion process. Consequently the free oxygen component of the exhaust will be a function of the excess air ratio at which the engine is operated.

2.1.1 Greenhouse Gases (GHG)

Carbon dioxide, CO_2, and water vapour, H_2O, are formed in all combustion process in which complete, or nearly complete, combustion of a hydrocarbon fuel takes place. Their relative proportions are determined primarily by the hydrocarbon composition of the fuel. Thus the production of both carbon dioxide and water vapour is a function of the quantity of the fuel burned, which to a large extent is determined by the plant

efficiency and the elemental composition of the fuel being burned. Although traditionally not regarded as a pollutant, carbon dioxide has become of increasing concern in recent times through its importance as a 'greenhouse gas' and the unknown consequences for the global climate of the trend of risingcarbon dioxide concentration. Inputs of water vapour (also a principal Greenhouse gas) to the atmosphere are, as yet, of little concern as the average global concentration is not believed to be changing. However, when applying various technologies to reduce NO_x emissions, the fuel consumption and as a consequence, CO_2 emissions tend to increase. The environmental impact of such an increase in carbon dioxide is another reason, apart from the financial consequences of the increased fuel consumption, why it is absolutely important that the development of NO_x reduction measures should not increase the fuel consumption.

2.1.2 Pollutant Emissions

The formation of oxides of nitrogen, NO_x, occurs as a result of the oxidation of molecular nitrogen in the combustion air and of organic nitrogen in the fuel. In the latter case, it would be expected that the bulk of the organic nitrogen will be oxidized during the combustion process. As heavy fuel oil has a greater content of organic nitrogen than marine diesel oil or other distillate fuels, the NO_x emissions of an engine running on heavy fuel are thus greater. The oxidation of atmospheric nitrogen is influenced by local conditions in the combustion chamber, such as for example the maximum cylinder pressure, local peak temperatures and local air-to-fuel ratios. Nitric oxide, NO, is a primary reaction product, but around five per cent of it is converted to nitrogen dioxide, NO_2, later in the combustion cycle, during expansion and during the flow through the exhaust system. At the same time, a very limited proportion of nitrous oxide N_2O is also formed. Further oxidation of NO to NO_2 subsequently continues at ambient temperatures after the exhaust gases have passed out to the atmosphere. The environmental effects of NO_x are diverse. Nitrogen oxide is of particular concern because of its detrimental effects on respiration and plant life, as well as its significant contribution to acid rain. In addition, NO_x, together with volatile organic compounds (VOC), is also involved in a series of photochemical reactions that lead to an increase in troposphere ozone which, in turn, adversely affects human health, crop yields and natural vegetation. It should be mentioned that these problems are only pronounced on land, and especially in urban areas. Nitrogen

oxides are one of the primary pollutants which have been introduced in regulations, such as those adopted by the IMO.

The oxides of sulphur, SO_x, derive directly from the sulphur content of the fuels used. In the combustion chamber, the sulphur is oxidized, thereby forming principally sulphur dioxide, SO_2, and, to a much lesser extent, sulphur trioxide, SO_3. The alkaline lubricants employed to protect the diesel engine liner surface from acidic corrosion convert a small proportion of the SO_X produced by the combustion process to calcium sulphate. However, this is a relatively insignificant proportion and the sulphur emissions from the engine will essentially be proportional to the sulphur content of the fuel and the fuel consumption. Sulphur oxides are the major source of acid rain. They thus have detrimental effects on plant life, vegetation, human respiration and buildings. On the other hand, it has to be stressed that the effect of acid rain on the sea is in most cases negligible. This is because sea water is slightly alkaline. One lt of sea water can, on average, neutralize some 300 mg of sulphur. It also seems that SO_x is only transported over a relatively short distance (some ten or at most 100km). Nevertheless, limitation of the emission of sulphur oxides has been introduced in the recent IMO regulations.

Carbon Monoxide, CO, is the result of incomplete combustion of carbonaceous material. Its formation in the diesel engine is thus principally a function of the excess air ratio, the temperature of combustion and the uniformity of the air/fuel mixture in the combustion chamber. In general, carbon monoxide emissions from large two-stroke diesel engines are lowowing to the high oxygen concentrations and the efficient combustion process. Broad environmental effects are not generally of major concern from carbon monoxide, although the gas may have some small influence on global climate change. Owning to the low level of carbon monoxide in exhaust gases, it has not so far been addressed in marine regulations.

The hydrocarbon fraction, HC, of the exhaust gases will predominantly consist of unburned or partially burned fuel and lubricating oils. In reality this fraction comprises a myriad of individual organic compounds with almost every chemically allowable configuration of carbon, hydrogen, nitrogen, oxygen and sulphur being represented, albeit at extremely low concentrations. Individual components may be present in either vapour or particulate phases, or may switch between the two phases through evaporation, condensation and polymerization reactions leading to a

constantly changing distribution. Consequently, the diverse nature of the hydrocarbon fraction components makes for difficulties in both quantifying the emissions and in identifying the specific health and environmental problems. In general, hydrocarbon emissions result from incomplete combustion. The nature and level of hydrocarbons in the exhaust will thus be largely dependent upon the combustion characteristics and thermal efficiency of the engine which, in turn, are influenced by engine load, condition and maintenance. With correctly-adjusted engines, hydrocarbons are emitted in very small quantities and thus present only a minor problem with respect to emissions in the marine environment.

The particulate fraction of the exhaust emissions represents a complex mixture of inorganic and organic substances largely comprising elemental carbon, ash minerals, heavy metals, condensed sulphur oxides, water, wear debris and a variety of unburned or partially burned hydrocarbon components of the fuel and lubricating oils. Particulates may potentially cause some respiratory problems, as well as more serious health effects. To a large extent, the magnitude of particulate emissions will be dependent upon the fuel oil quality and the completeness of combustion with 'smoke' traditionally acting as a criterion of combustion quality. Yet smoke is simply a visual criterion and does not necessarily imply that the engine is polluting. For example, white smoke is usually condensing water vapour and some real pollutants are in fact invisible. Quantification of the particulate emissions is difficult on account of their complex nature. Thus, a variety of terms are employed to describe both the nature and quantity of particulate matter. Many terms are defined by sampling and quantification methods, and include suspended particulate matter and total suspended particulates. [1]

2.2 NOx Emission Formation in Marine Diesel Engines

Nitric oxide from combustion originates from two sources: atmospheric nitrogen (N_2) in the combustion air and organic nitrogen in the fuel (N_{fuel}). Typically, N_2 is the most important source in diesel engines. If the fuel contains a significant amount of organic nitrogen – in the range of above 1 %-wt, as certain fuel oils do, the final NO emission may typically increase by about 10-30%. During devolatilization the organic nitrogen in the fuel is released, and rapidly forms smaller nitrogen compounds like hydrogen cyanide (HCN) and ammonia (NH_3). All the main reactions and their kinetics for gas-

phase formation of NO from N_2, HCN, and NH3 are currently well known, as illustrated in a simplified way in Figure 2.
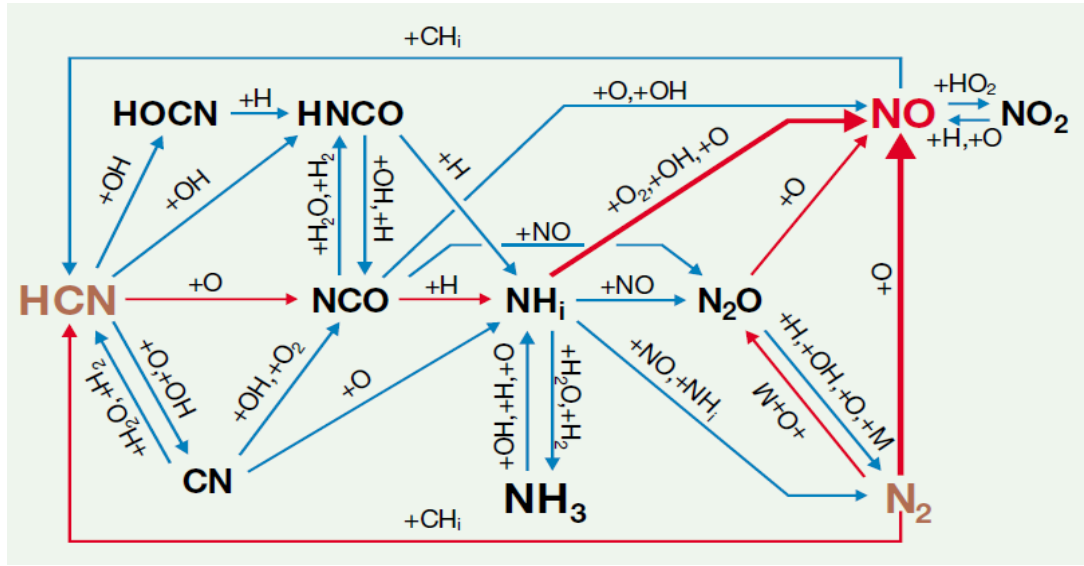
Figure 2. Simplified scheme of the main reactions in the formation and destruction of nitric oxide during combustion [36]

From atmospheric nitrogen (N_2) the three most important routes for NO formation are thermal NO, prompt NO, and nitrous oxide NO.

2.2.1 Thermal NO

Formation of nitric oxide from molecular nitrogen requires breaking the strong triple bond between the nitrogen atoms in N_2. An oxygen molecule (O_2) is not capable of breaking this bond under combustion conditions, because even at higher temperatures a direct reaction between molecular nitrogen and molecular oxygen takes place too slowly:

$$N_2 + O_2 \leftrightarrow 2NO \ (-)$$

Instead, the formation of nitric oxide from molecular nitrogen takes place through a chain reaction mechanism. This reaction is initiated by a nitrogen molecule (N2) and an oxygen atom (O):

$$N_2 + O \leftrightarrow NO + N \quad (R1)$$

$$N + O_2 \leftrightarrow NO + O \quad (R2)$$

The reaction mechanism R1 + R2 was first introduced in the 1940s. This mechanism is called the Zeldovich mechanism. It has been observed later that, with less excess air

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and under sub-stoichiometric (reducing) conditions, the effect of O2 as an oxidizer of nitrogen atoms (reaction R2) is reduced. The nitrogen atoms released at reaction R1 are then oxidized to nitric oxide mainly by a hydroxyl radical (OH):

$$N + OH \leftrightarrow NO + H \, (R3)$$
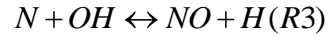
This reaction mechanism R1 + R2 + R3 is known as the extended Zeldovich mechanism. Reaction R1 has very high activation energy and is the factor limiting the reaction rate of the Zeldovich mechanism. It also makes the mechanism extremely sensitive to temperature. For this reason the nitric oxide formed according to the Zeldovich mechanism(s) is commonly known as thermal NO. As calculated, the formation rate of thermal NO is practically insignificant if the temperature is below 1700 K. On the other hand, if the temperature rises, especially over 2000 K, the formation of thermal NO is strongly accelerated. The formation of thermal NO may be reduced by lowering and controlling the temperature peaks ('hot spots') and minimizing flue gas residence at high temperatures. Suitable methods for lowering temperature peaks include direct steam injection into the cylinder, dilution of the intake air with re-circulated exhaust gases, and humidification of the intake air with steam.

2.2.2 Prompt NO

In the 1970s Fenimore [3] showed that not all nitric oxide formed in, especially, sub-stoichiometric hydrocarbon flames could be explained by Zeldovich mechanisms. He suggested that the nitrogen in the combustion air reacts to NO through another mechanism, which is initiated by a reaction between N_2 and hydrocarbon radicals (CHi):

$$N_2 + CH \rightarrow HCN + N \quad (R4)$$

If oxygen-containing components are present, the hydrogen cyanide (HCN) and the nitrogen atom (N) produced in the reaction react further to nitric oxide through several reaction phases. Under most conditions, the main reaction sequence is:

Formation of nitric oxide according to the above mechanism occurs only in a combustion zone of the flame where the combustion is incomplete and hydrocarbon radicals necessary for reaction R4 are present. The formation of nitric oxide is usually very fast, and the nitric oxide formed is therefore called prompt NO. In contrast to

thermal NO, fast NO depends only slightly on temperature. In diesel engines, the contribution of prompt NO to the total NO emission is estimated to be minor, below 5%.

2.2.3 Nitrous oxide NO

A third mechanism for reaction of molecular nitrogen to nitric oxide was presented in the 1970s [3]. According to this mechanism, atomic oxygen (O) and N_2 form an unstable gas (N_2O, 'laughing gas') according to the following reaction:

$$O + N_2 + M \leftrightarrow N_2O + M \quad (R6)$$
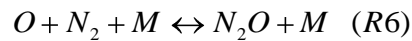
where M represents any gas component. The laughing gas formed reacts again, either back to N_2 or to NO, depending on conditions. Generally, formation to molecular nitrogen governs. However, when the air ratio and temperature increase, the formation of nitric oxide also increases. The main reaction to nitric oxide is then:

$$N_2O + O \leftrightarrow 2NO \quad (R7)$$
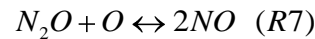
The significance of nitrous oxide NO for NO emission from diesel engines is at present not entirely clear. Only the recent progress made in kinetic modelling of nitrogen reactions has brought this mechanism (R6 + R7) for nitric oxide formation into focus.

2.2.4 Fuel NO

From fuel-nitrogen (HCN) the most important NO formation route is the reaction (R8). It is identical to a part of the (R5) reaction in the prompt NO mechanism. Fuel NO is slightly dependent on temperature, and nitric oxide is easily formed from fuel-nitrogen at low temperatures too, below 1100 K. [3]

$$HCN \xrightarrow{+O} NCO \xrightarrow{+H} NH \xrightarrow{+H} N \xrightarrow{+O_2,+OH} NO \quad (R8)$$
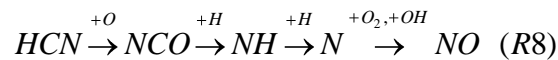
2.3 Carbon Dioxide from Marine Diesel Engines

The reaction of a hydrocarbon fuel with oxygen in the combustion process releases carbon dioxide, water and energy. There is no alternative in the process of releasing the energy from a hydrocarbon fuel. Carbon dioxide released is directly proportional to the amount of energy released. The amount of carbon dioxide released by hydrocarbon fuels depends a great deal on the molecular structure of the fuel.

Liquid petroleum fuels release more carbon dioxide for the same amount of energy because of the lower hydrogen to carbon ratio followed by coal with the most carbon dioxide because it approaches pure carbon.

While there is ongoing discussion about the effect of carbon dioxide on global climate change, carbon dioxide in the upper atmosphere has almost doubled from 250 ppm in 1750 to 450 ppm today. The general practice isis that the reduction offuel consumption and the protection of the environment is good for world economies regardless of the direct effect of carbon dioxide levels in the upper atmosphere on climate change.

The theoretical efficiency of energy release in a chemical reaction can be calculated from the following equation:

$$Theoretical\ Energy\ Efficiency = \frac{T_{Combustion} - T_{Exhaust}}{T_{Combustion}}$$

where T is in degrees Celcius. . At $2500^{o}C$ combustion temperature and for $500^{o}C$ exhaust temperature, the theoretical efficiency will be 80%.

In practice, the efficiency of energy in fuel into an engine compared with power out is much different. Ultra low-speed diesel engines reach up to 55% efficiency. A medium- or high speed compression-ignited reciprocating engine (Diesel) is in the 40 – 45% range and a spark-ignited reciprocating engine (gasoline) is in the 25 – 30% range. [4]

2.4Particulate Matter from Marine Diesel Engines

Particulate matter (PM) is smoke or soot emanating from the engine exhaust. Particulate matter is partially burned hydrocarbon material that is in the condensed aromatic form.

It is similar to graphite and resembles sheets of carbon joined in a hexagonal form. These molecules have unsaturated bonds that result in sharing of electrons. These types of molecules cause free radical formation and are highly carcinogenic. Mice on verges of highways have high incidences of pulmonary tumors caused by PM's. In actual practice on a ship, high levels of soot result in oily material on the ship with a low pH from entrained sulfuric acid. It is not only a health hazard, but is difficult to

clean and remove. It is highly corrosive to metal. Ship personnel complain that the material is tracked all through the ship.

PM's can be measured quantitatively by passing a measured sample of exhaust gases through a filter for a period of time and weighing the retained material. Filters are limited to 2 micrometer (micron) size range. The resulting measurement is only for particulate matter of greater than 2 micron in size. The human eye can see light in the 0.4 to 0.7 micron wavelength. As a result, we can see particles down to 0.4 microns in size. Therefore, the actual level of PM is a multiple of the measured amount by this method. PM measurements range from a few milligrams to 2,000 milligrams per cubic meter of exhaust gas. The latter would be typical of a truck Diesel smoking heavily under load. [4]

2.5 Sulphur Oxides from Marine Diesel Engines

Sulphur is a naturally occurring element in hydrocarbon fuels. It is associated with asphaltenic fuels and correlated with vanadium content. Sulphur generally occurs in large aromatic molecules. Because of this, it is concentrated in residual oils or HFO.

In the combustion process, sulphur forms sulphur dioxide (SO_2). This compound is relatively benign. However, it enters an equilibrium reaction with oxygen to form O3 which combines with water to form sulphuric acid (H_2SO_4). The chemical reactions are as follows:

$$S^{-2} + O_2 \rightarrow SO_2$$
$$SO_2 + 1/2O_2 \leftrightarrow SO_3$$
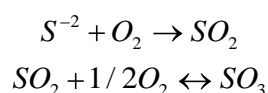
This equilibrium is the key to controlling sulphuric acid formulation. The mathematical expression for the equilibrium is:

$$K = \frac{[SO_3]}{[SO_2][O_2]^{1/2}}$$

where K equals to 0.1 in most cases. Iron surfaces catalyze the formation of SO3 increasing the value of K. Magnesium oxide reduces the value of K, perhaps by coating iron surfaces or by catalyzing the formation of SO_2. Formation of SO_3 requires oxygen.

Operation under reduced excess air conditions will reduce sulphur trioxide formation.

Once SO_3 is formed, it will react with water to form sulphuric acid as follows:

$$SO_3 + H_2O \rightarrow H_2SO_4$$
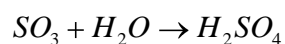
If magnesium oxide or calcium oxide are present in the exhaust stream, they will react with sulphuric acid to form neutral calcium and magnesium sulphate salts.

$$H_2SO_4 + MgO \rightarrow MgSO_4 + H_2O$$

$$H_2SO_4 + CaO \rightarrow CaSO_4 + H_2O$$
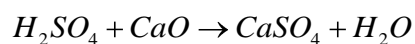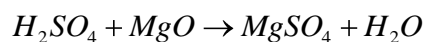
There is a strong effort being made to remove sulphur from fuel. The current limit for ships operating within Emission Control Areas is 1.5% sulphur. Examples of these areas are a proposed 200 mile nautical limit around the U.S. and Canada, and the North Sea. These limits are expected to fall to 1.0% in July 2010 and 0.10% in January 2015. The latter level is the same as Low Emission Diesel (LED) currently available at the pump in the United States. [4]

3 CLIMATE POLICY: ANALYSIS FOR INTERNATIONAL MARITIME TRANSPORT

3.1 General Information

Ship transportation is considered the most environmentally-sound mode of transport. In public opinion, environmental problems of ships seem to be linked to accidents, in particular of oil tankers. Emissions of local and global air pollutants through the burning of marine bunker fuels are a relatively new area of environmental concern. Thus, the emissions of the international merchant fleet have become an increasing focus of global and regional environmental policies. The integration of the shipping industry into the global climate policy regime is currently a new challenge for policy makers and the industry.

Climate protection has to be considered as a cross-sectional policy area, dependent on the coherence of environmental objectives in related policy areas, such as transport or trade regulation. In the last decade, international climate policy has become one of the most important elements of national and international environmental policies. International negotiations on climate change started in the late 1980s and resulted in the signatory of a Framework Convention on Climate Change (FCCC) at the UN Conference on Environment and Development in 1992 [5]. They culminated in the negotiation of the Kyoto Protocol in 1997. It will be the initial step towards a comprehensive global greenhouse gas regime. Bunker fuel emissions account for about 1.8 % of the world's CO_2 emissions in 1998 and are thus in the magnitude of OECD countries like France (1998: 1.6%) or Australia (1998: 1.4%) Bunker fuel emissions from international shipping and emissions from air transport have so far been excluded from any commitment in the Kyoto Protocol. While emissions from international aviation have been targeted by many environmental NGOs, and been subject of a special report of the Intergovernmental Panel on Climate Change (IPCC), international shipping has so far been neglected in the debate. However, corresponding to the discussion on aviation, air emission from ships is likely to be integrated into the existing climate regime over the next years. This is all the more true against the background of the successful climate negotiations in July 2001 that paved the way to an international ratification of the Kyoto-Protocol. After looking at the magnitude of emissions from international shipping and likely trends, we make

suggestions how this integration can be done in an economically efficient and politically feasible way.

Parallel to the debate on climate policy, international shipping is already experiencing the first effects of global warming. Ports in northern Canada are able to expand their shipping season and ship owners are exploring Arctic routes in order to bypass bottlenecks on established routes or to cut down on travel time. But the forecasted increase in stormy weather and the consequences of a sea level rise for ports make it unlikely that shipping will belong to the winners of climate change.

3.2 International Climate Policy and Shipping

Scientists have warned about a potential impact of human activities and in particular of the burning of fossil fuels on the global climate system for several decades before political negotiations started on an international level in the late 1980s. Today, there is a general consensus on the existence of an anthropogenic warming of the global atmosphere and the necessity of an international climate regime to limit the emission of greenhouse gases, such as carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphur hexafluoride (SF6).

The most important GHG is carbon dioxide, particularly as exhaust gases from the combustion of fossil energy. The source of GHG emissions growing most quickly are transport services; in the industrialized countries they increased by over 13% between 1990 and 1998). The Framework conventrion on climate change (FCCC) was the launching pad for stronger action in the future. By establishing an ongoing process for review, discussion, and information exchange, the Convention makes it possible to adopt additional commitments in response to changes in scientific understanding and political will. The third conference of parties to the FCCC held in December 1997 in Kyoto, Japan adopted a Protocol with targets for industrialized countries' (so-called Annex B countries) greenhouse gas emissions. These targets range from -8% for the EU to +10% for Iceland compared to 1990 levels by the period 2008 – 2012. Developing countries have no targets. In July 2001, the part sixth conference of parties was continued in Bonn, Germany (COP 6bis). All crucial questions about the exact design of the four flexible mechanisms in the Kyoto Protocol were resolved and a sufficient number of relevant countries declared that they will now ratify the

Protocol. Industrialized countries will thus be enabled to trade emission reductions internationally and use least-cost options for emission reductions on global markets instead of reducing emissions by internal measures.

3.3 Impacts of climate change on international shipping

Climate change is likely to have substantial impacts on the oceans and thus on international shipping. These impacts are not necessarily negative. Both the impacts on infrastructure (port facilities) and ships have to be considered.

Sea-level rise and increased storminess will have enormous impacts on ports. If the current infrastructure at the land/sea interface is to be protected, extremely high costs are to be expected. For example, as it may cost 63 billion US$ to protect only Japanese ports. Dredging of waterways is already an important cost factor and considered as the most serious environmental problem for ports. Increased runoff and precipitation will lead to a higher sediment load of rivers. Demands for dredging operations thus can be expected to increase and lead to an increase in costs in ports. A sea-level rise, induced by global warming, is unlikely to compensate silting of waterways. If the frequency and intensity of extreme weather conditions and in particular of tropical storms and cyclones increases, tropical routes become more dangerous, and higher losses can be expected.

Weather conditions might force ships to change routes or speed, or to stay longer within protected areas. If the number of lost ships, the damage to ships, or the loss of cargo increases, insurance companies will reflect the higher risk level in their rates or compensation levels. Consequently, ship operators will face increase costs in any case: Either due to higher losses or in form or higher insurance fees.

But global warming will also lead to positive effects for international shipping, like the reduction of sea ice. Costs for icebreakers which can amount to annual double-digit million dollar figures for countries like Canada or Russia could be reduced. Both the Northwest Passage and the Northern sea route around Russia are likely to be opened up for routine shipping in the next decades. Currently, high insurance costs, the iceberg threat, the need for icebreakers and expensive reinforced hulls, and the extremely short open-water season limit the traffic on Arctic routes. Furthermore, Arctic routes would reduce freight costs from East Asia to Europe considerably. Ships taking cargo from Rotterdam to Yokohama could cut 5,000 miles, almost cutting

travel time in half from the Panama route. Using a route north of Russia similarly nearly halves the time and distance compared to the Suez Canal route between Hamburg and Yokohama. It goes without saying that ship operators will take advantage of these effects while environmentalists may point out the possibility of further damages to these regions.

3.4 Factors influencing pollutant emissions by ships

Freight rates have shown a steady downward trend since the beginning of the 1980s, and sometimes freight rates have not covered the operational costs. Ship-owners have developed different strategies to cut costs wherever possible. One way to do this is through registration in open registers. While the majority of all vessel transport is linked to trade between industrialized countries, an increasing share of the merchant tonnage is registered outside of the main trading countries, in open registers.

Since the beginning of the 1980s the OECD (Organization for Economic Co-Operation and Development) registered tonnage has declined from 51% of the world tonnage to 24.4% by the end of 1999 [5]. A large share of this decline is the result of the introduction of open registers and the OECD flagging-out. Flagging-out aims at minimizing operational costs and regulatory requirements. While it helps ship-owners from OECD countries to compete on the global market, it promotes a race towards substandard shipping.

In addition to flagging-out, ship-owners have passed their responsibility for asset marketing and day to- day operation to ship management organizations. In many cases the focus of such a management company is on commercial aspects, neglecting aspects related to the safe operation of the ship. Cost cutting has induced reckless loading practices in ports and operation at a higher speed, sometimes beyond permissible design limits.

Over the last 35 years remarkable improvements in fuel efficiency have been achieved, for instance by engine optimization. However, the highest priority for potential ship owners is the capacity and the speed of the vessel. Energy efficiency and environmental impact are of minor importance as long as no conflict occurs with international or regional legislation over the ship's lifetime, or as long as there are no economic incentives (e.g. graded port fees, taxes etc.).

GHG emissions from ship operations are often linked with emissions of other pollutants that create important environmental problems. Table 2 gives an overview of these links. [5]

Table 2. Gaseous pollutants from ships and its environmental effects [37]

POLLUTANTS CONSEQUENCES	SOx	NOx	VOCs	CO_2	CFCs	Halons	CH_3Br
Greenhouse effect				X	X	X	
Ozone-stratospheric					X	X	X
Ozone-ground level		X	X				
Acid rain	X	X					
Linked-up with:							
Fuel combustion	X	X	X	X			
Cargo handling			X		X		X
Ship's equipment					X	X	
Incinerators	X	X		X			

3.5 Economic instruments for reducing emissions from sea transport

In June 1998 a joint Transport/Environment Council [5] called for measures to make the best use of existing infrastructure, to achieve a shift to less environmentally damaging modes of transport, and the use of economic instruments to reduce fuel consumption, emissions and noise.

3.5.1 The White Paper on infrastructure charging

In July 1998 the European Commission presented its White Paper Fair payment for infrastructure use: a phased approach to a common transport infrastructure charging framework in the EU.[5] The White Paper recognizes the need for a pricing system that is based on short term social marginal costs, including for instance the costs of congestion, transport accidents and exhaust emissions. The Commission wants these principles to be applied to all four modes of transport to avoid a negative impact on competitiveness and the distortions of the single market caused by the many shortcomings of today's pricing system, including taxes and charges.

Within a framework based on common principles Member States would to a large extent be free to set charge levels. Should pricing based on short-term social marginal costs not lead to recovery of infrastructure capital costs and Member States wish to arrive at a higher level of cost recovery, then the Commission considers this should be done through the imposition of additional non-discriminatory and non-distorting fixed

charges. The Commission concludes that the co-ordination of transport charging and the development of efficient charging levels is expected to produce a small desirable change in modal split and a small reduction in the growth of demand for mobility. Most of the adjustment will take place within each mode of transport, and Commission studies suggest that the new pricing system would lead to overall welfare benefits in the order of at least 30-80 billion Euro per year.

The Commission proposes a step-by-step approach to the implementation of common principles for infrastructure and externality charging. After a preparatory phase (1998-2000), the second phase (2001-2004) is intended to involve adapting particular charges to better reflect real costs and to harmonize charging systems between modes. Charging levels for externalities having a Community dimension should, according to the White Paper, be set at Community level, probably at an agreed low rate to begin with. During the third phase (beyond 2004) the harmonized charging principles should be further implemented, both in terms of the marginal cost basis and the consistency of cost estimation.

The White Paper says maritime shipping has comparatively low infrastructure and external costs, although emissions of sulphur and nitrogen oxides are significant and give rise to concern. Therefore the first phase should include consideration of emissions from shipping in the context of ongoing international discussions on the matter. In the second phase, consideration should be given to the introduction of minimum fuel standards, and the Commission will also consider the feasibility of levying environmental fuel charges that vary according to emissions. Alternatively, fairway charges could be introduced and differentiated on the same basis.

The first phase of the work has to a large extent been carried out by a High Level Group on Infrastructure Charging. However, the High Level Group's final report on estimating transport costs does not add much to what had already been accomplished by the White Paper. Neither the final report nor the four background papers make any reference to shipping [5].The Commission has recently commissioned a consultant to carry out a study of the economic, legal, environmental and practical implications of the European Union system to reduce ship emissions of SO2 and NOx, which is expected to be finalised by the end of 1999.

3.5.2 Green Paper on sea ports and maritime infrastructure

Prior to the White Paper, the Commission in 1997 presented a Green Paper on Sea Ports and Maritime Infrastructure [5]. The reason for publishing a Green Paper came from the fact that the completion of the internal market has intensified competition significantly among ports. The Commission wants to avoid open or hidden subsidies that give rise to trade distortions. It therefore says port charges should be set in line with marginal costs and also take into account new investments.

The Green Paper, however, is hesitant about charging shipping the full marginal cost of maritime access. It notes that a number of European ports, mainly those on the North Sea, are located on river estuaries or are river ports subject to chronic silting. This gives rise to substantial outlays for dredging, which are at present in most cases publicly funded. Although there is no *a priori* reason why marine access should be treated differently from other infrastructural costs, the Commission thinks the recovery principle should in this case be approached with caution. The Green Paper notes that navigational aids, such as lighthouses and buoys, have traditionally been seen as public goods. Now the Commission proposes that common principles should be established for recovering the development and investment costs of aids for coastal navigation.

3.5.3 European Sea Port Organization Policy

The General Assembly of ESPO, the **European Sea Port Organization**, has endorsed the following policy on differentiated charging, arising out of a proposal from its Environment Committee:

- As responsible organizations committed to environmental progress, ports should consider the scope for using price mechanisms to achieve environmental improvements and/or other benefits. This could be one of a number of measures aimed at improving the environment.

- ESPO will review existing and future schemes to assess their effectiveness in achieving their objectives and their compatibility with port charging structures.

- The use and construction of differential charging must be entirely the decision of the port concerned, as mandatory differential charging schemes are unlikely to take account of both the commercial realities of port operation and the principles

of .user pays. and polluter pays. Otherwise the result could be that ports find themselves subsidizing the shipping sector, which is not acceptable. [6]

4 MARITIME ENVIRONMENTAL REGULATIONS

4.1Regulations and Incentives

In September 1997, the International Maritime Organization (IMO) adopted an international convention protocol to reduce air pollution from ships, in order to achieve sustainable maritime development. This protocol has been approved by 15 member countries and will be enforced in May 2005. Pollutants emitted from ships, such as nitrogen oxides, volatile organic compounds, sulfur oxides, etc. will be regulated by this convention through ship inspections and issuance of certificates. Ships belonging to maritime countries such as Taiwan, which sail around the world and berth in commercial ports, must obey this convention. This study has investigated possible strategies, which may be adopted by maritime countries to conform to this IMO convention in order to reduce the air pollution from ships. A sea-going ship must prepare EIAPP and IAPP certificates for inspection by port-state-control officials, when the ship is anchored at a maritime port. These port-state-control officials may also require the continuous detection and sampling of a ship's emissions, while it is berthed at the port. Legislative support is necessary for successful implementation of these safeguards. It is suggested, therefore, that the administration of both navigational and environmental protection, in maritime countries, cooperate in the revision of relevant federal laws, to implement the provisions of the MARPOL 73/78/97 convention; in this way, the air pollution from ships can be effectively controlled. Installation of advanced detection equipment can effectively detect any ships' violations of air pollution regulations. The Harbor Affairs' Bureau should also establish a database of air pollution inspections for ships berthed within their harbor, requiring that ships' equipment comply with the requirements of the MARPOL convention, for the reduction of air pollution.

Promoting maritime traffic safety, while protecting the ocean environment, are important concerns in the global maritime field. Because more than 50% of a ship's operating expense is generally the cost of fuel oil, most of the world's ship-owners use degraded residue heavy fuel oil in marine power plants, for fuel economy. These degraded heavy oils, however, contain high levels of asphalt, carbon residues, sulfur (which may amount to as high as 5 wt.%) and metallic compounds, as well as having properties of high viscosity (up to 700 cst), low cetane numbers and low volatility .

During the burning process in marine diesel engines, boilers, and incinerators, these fuels can produce significant amounts of black smoke, particulate matter, nitrogen oxides (NO_X), unburned hydrocarbons (UHC), sulfur oxides (SO_X), carbon monoxide (CO), carbon dioxide (CO_2), etc. These pollutants, which may deplete the ozone layer, enhance the green-house effect, and produce acid rain are detrimental to the health of living beings and have attracted a great deal of public concern.

There are great differences between marine vessels and land vehicles, in respect to the fuel used and the size and horsepower of the engines. The emission control requirements for road vehicles are not suitable for marine vessels; thus, the emission control strategies and pollution prevention technologies applicable to ships must be given special consideration to effectively reduce the air pollution from ships.

The International Maritime Organization (IMO) is responsible for drafting various international conventions related to maritime affairs, with regulations covering navigation, marine rescue, and ships' structural and equipment requirements. There are currently more than 150 countries belonging to the IMO, which is the most powerful international organization in the field of ocean shipping. The objectives of the IMO include sustaining safety in sea transportation, promoting navigational efficiency, and protecting the ocean environment. The Marine Environment Pollution Committee (MEPC), which is a sub-organization of the IMO, is specifically responsible for drawing up relevant regulations to prevent ships from polluting the ocean and the atmosphere. [7]

4.2 What is MARPOL

MARPOL arose out of the efforts of the International Maritime Organization (IMO), a specialized agency of the United Nations, to protect the environment from operational and accidental pollution from ships. The IMO utilizes conventions, codes, and guidelines to address international maritime issues. Member States are encouraged to ratify these conventions and incorporate the standards into their domestic legislation. The IMO believes that it can best accomplish its goals of safety, efficiency, and cleanliness by creating standards that all shipping nations adopt and adhere to.

MARPOL emerged in the 1970's from a combination of two treaties. The first convention, adopted by the IMO on November 2, 1973, covered pollution from oil, chemicals, sewage, garbage, and harmful substances in packaged form but never went into effect. IMO conventions must be ratified by a particular number of States representing a certain percentage of the world's shipping fleet before they will come into force. The 1973 Convention required ratification by fifteen States with a combined merchant fleet representing over fifty percent of the world's shipping. As of 1976, just three States representing less than one percent of the world's merchant shipping fleet had ratified the 1973 Convention. In time, a 1978 protocol did eventually enter into force on October 2, 1983 and it absorbed the parent convention.

MARPOL contains six Annexes addressing specific areas of concern to the international maritime pollution problem:[8]

1. **Annex I:** Regulations for the Prevention of Pollution by Oil and Annex II: Regulations for the Control of Pollution by Noxious Liquid Substances in Bulk became effective on October 2, 1983.

2. **Annex III:** Prevention of Pollution by Harmful Substances Carried by Sea in Packaged Form entered into force in July 1992.

3. **Annex IV:** Prevention of Pollution by Sewage from Ships became effective on September 27, 2003

4. **Annex V:** Prevention of Pollution by Garbage from Ships on December 31, 1998.

5. **Annex VI:** Prevention of Air Pollution from Ships, which is the main focus of this paper, took effect on May 19, 2005.

4.3 MARPOL Annex VI Regulation

Annex VI regulates emissions of NOx and SOx, prohibits intentional emissions of ozone depleting substances, regulates onboard incinerators, and sets standards for tanker vapour emissions. Annex VI does not distinguish between recreational and commercial vessels, or between international and domestic vessels. A vessel is only exempt from compliance when assisting with rescue operations or if suffering from damage caused without the fault of the vessel operator.

Annex VI seeks to limit emissions of NOx and SOx by establishing standards concerning emissions and fuel content. Under Annex VI, NOx standards apply to marine engines rated above 130 kW if the vessel was constructed, or the engine has undergone major conversion, on or after January 1, 2000. Annex VI relates NOx emissions standards to engine-rated crankshaft speed.

Table 3. NOx emission Limit- Annex VI [8]

Engine Speed	NOx Emission Limit (g/kWh)
Less than 130rpm	17.0
130 – 1999rpm	45.0 X [Engine Speed]$^{-0.2}$
2000rpm and above	9.8

The NOx Technical Code outlines the testing parameters for compliance with Annex VI standards. Regulated vessels can meet NOx standards by utilizing exhaust gas cleaning systems or any other equivalent method that will reduce emissions to within the specified range.

Sulfur content in fuel is limited to 45,000 parts per million (ppm) irrespective of fuel grade or machinery used. The IMO is required to monitor the worldwide sulfur content average. Suppliers must document sulfur content of the fuel in a bunker delivery note, which must be retained onboard the vessel for a period of three years along with a representative sample of the fuel that must be retained for twelve months. In special SOx Emission Control Areas (SECA) the sulfur content in fuel cannot exceed 15,000 ppm. Ships burning fuel with higher sulfur content may enter a SECA only if the engine has been outfitted with an exhaust cleaning system or other technology such as segregated bunker capacity and the ability to switch upon entering to lower sulfur fuel. State parties can propose new SECAs which are evaluated based on the costs of reducing sulfur from ships compared to land-based control as well as the impacts on shipping and trade. Amendments to Annex VI established the Baltic Sea SECA in 1997 and the North Sea SCEA in 2005.[8]

Compliance with Annex VI is the responsibility of vessel owners/operators. Enforcement of MARPOL is the responsibility of signatory States acting within their own jurisdictions. Enforcing parties conduct surveys to ensure that vessels and engines comply with the requirements of Annex VI. Survey requirements apply to vessels over 400 gross tons and to floating drilling rigs and other platforms. If a vessel meets the Annex VI criteria, the surveying State issues an International Air Pollution

Prevention Certificate (IAPP). If a vessel is determined to be operating with equipment not corresponding with the IAPP, the State with jurisdiction over the waters in which a vessel is operating may take action.

Vessel surveys take place throughout the life of a vessel and include[8]:

- Initial surveys occurring before the ship enters service or before issuing an IAPP for the first time to ensure that the equipment complies with the standards;

- Periodic surveys occurring at least every five years after the initial survey to ensure that no modifications have been made that would take equipment out of compliance and require the re-issuance of the IAPP;

- Intermediate surveys occurring at least once during the period between issuance of an IAPP and the periodic surveys to ensure that equipment is still compliant;

- Unscheduled surveys occurring periodically, unless annual periodic surveys are required, in which case unscheduled surveys are not obligatory;

- Pre-certification surveys occurring prior to an engine instalment onboard a vessel to ensure compliance with NOx limits (An engine meeting the standards will be issued an Engine International Air Pollution Prevention Certificate (EIAPP) in accordance with the NOx Technical Code.);

- Re-survey/certification is required (1) if inspections and surveys are not carried out within the specified periods; (2) if significant alterations occur to the equipment, systems, fittings, arrangements or material to which Annex VI applies; or (3) upon transfer of the ship to a flag of another State; and

- Cautionary inspections may be conducted if there are grounds to believe that the vessel's master or crew is not familiar with essential procedures relating to prevention of air pollution.

- While ships are on international voyages, they must carry their IAPP onboard, which serves as prima facie evidence that the ship complies with the Convention. To be IAPP compliant, ships must possess the EIAPP or Statement of compliance, in addition to a Technical File, and a Record Book of Engine Parameters. If there are clear grounds for believing the ship is not compliant with Annex VI or its certificates, or if a ship does not possess a certificate, the enforcing party may

detain the ship until satisfied that it can travel to sea without unreasonably harming the environment. [8]

In summary, the provisions of *MARPOL Annex VI* are[8]:

- 2005 Tier1 NOx for new engines post 2000

- 2010 ECA fuel sulphur 1% (currently 1.5%)

- 2011 global Tier 2 NOx for new engines (IMO Tier 1 less 15 to 20%) (engine tuning)

- 2012 global fuel sulphur 3.5% (currently 4.5%)

- 2015 ECA fuel sulphur 0.1%

- 2016 ECA Tier 3 NOx for new engines (IMO Tier 1 less 80%) (exhaust gas aftertreatment)

- 2020 global fuel sulphur 0.5% - if refineries can produce it, review in 2018

- Tier 1 NOx for engines greater than 5MW installed 1990 to 2000 (conversion kits)

- Under *Annex VI*, exhaust gas scrubbers can be used as an alternative to low sulphur fuel.

- Reduced sulphur content will reduce fine particulate emissions significantly. [9]

4.4 EPA Regulation of Air Pollution from Ships

Under the Clean Air Act, the EPA (US Environmental protection agency) has a duty to protect air quality from all harms, including marine diesel engine emissions. Section 213(a) [3] of the Clean Air Act instructs the EPA to set standards that achieve the greatest emission reductions through the use of the best technology available to the regulated industry. The EPA reviews and revises the standards periodically in light of industry developments and effectiveness.

When dealing with marine diesel engines, the EPA divides engines into three categories based on per-cylinder displacement:

1. Category 1 engines have "a rated power greater than or equal to 37 kW and a specific engine displacement less than 5.0 liters per cylinder''.

2. Category 2 engines have "a specific engine displacement greater than or equal to 5.0 liters per cylinder but less than 30 liters per cylinder."

3. Category 3 includes the largest engines with per cylinder displacement greater than or equal to 30 liters.

Standards and regulations pertaining to marine engines get progressively stricter in intervals, called Tiers, which increase numerically starting at Tier 1. As technology improves and the EPA determines that technology warrants a stricter standard, the next Tier of standards enters into effect. Existing Tiers reflect the IMO's work under Annex VI; however, Annex VI was not binding in the U.S. when the Tiers went into effect.

In 1999, the EPA promulgated a rule entitled Control of Emissions of Air Pollution from New Compression-Ignition Engines at or above 37 KW.The new regulations governed both propulsion and auxiliary engines.58 Although the rule did not adopt the Annex VI standards, the EPA encouraged manufacturers, through voluntary measures referred to as Tier 1 standards, to build engines that were compliant with Annex VI. The EPA also adopted a schedule for future implementation of a set of mandatory Tier 2 standards for Category 1 and 2 engines that would be similar to the standards for land-based diesel engines.[8]

Notably, the EPA expected Category 3 engines to meet voluntarily the Annex VI standards and did not establish a schedule for implementation of stricter standards. This resulted in the largest engines being left without finalized emission standards. In addition, the 1999 Rule included a Foreign-Trade Exception applicable to all U.S. vessels that spent less than 25% of their total operating time within 320 km of U.S. territory and to vessels not operating between two U.S. ports. This exception also allowed qualifying vessels with Category 3 propulsion engines to exempt other onboard auxiliary Category 1 and 2 engines from national emission requirements. This created a loophole that allowed some vessels to operate their propulsion and auxiliary engines while in U.S. jurisdiction without regulation.[8]

A lawsuit over the EPA's decision to leave the largest engines unregulated resulted in a court settlement requiring the EPA to develop Category 3 NOx emission limits. In 2003, the EPA established Tier 1 emission standards for Category 3 engines flagged or registered in the U.S. Compliance was mandated by 2004. The Tier 1 NOx

emission standards were equivalent to the Annex VI limits, and were to be achieved using engine-based controls without the need for exhaust treatment. The rule also committed the EPA to more stringent Tier 2 standards for Category 3 engines by April 27, 2007. The 2003 rule also abolished the 1999 Rule's Foreign-Trade Exception.[8]

The 2003 Rule is applicable to owners, operators, and manufacturers of marine diesel engines. Unlike Annex VI, which targets ship owners and operators, the EPA rule focuses on manufacturers. The EPA requires ship operators to operate the engine within the certifiable parameters (including adjustable parameters) and maintain all records of maintenance, repair, and adjustment as it relates to emissions. The vessel owner must complete an annual compliance statement.

Most of the burden of the 2003 Rule falls on engine manufacturers. To certify their engines, manufacturers must:[8]

- Divide engines into "engine families" with similar characteristics;

- Test the highest emitting engine configuration within the family;

- Determine deterioration rate for emissions and apply that rate to the "zero-hour" emission rate;

- Determine the emission-related maintenance that will be necessary to keep the engines in compliance;

- Submit the test data to the EPA in an "application for certification;"

- Demonstrate prior to production that engines will comply throughout their useful life;

- Warrant to purchasers that engines will comply throughout their useful life; and

- Specify how the operator should adjust the engine and testing protocols.

Engine manufacturers who were already complying with the Annex VI NOx Technical Code specifically needed to examine their methods of emission testing to ensure compliance with the EPA regulatory scheme.

The EPA justified the short lead-time between announcement of the 2003 rule and the 2004 compliance date based on the fact that manufacturers were already meeting Annex VI standards and, therefore, already Category 3 Tier 1 compliant. The EPA

chose not to initially set standards higher than Annex VI because of possible delays in achieving greater environmental benefits including: recognition that manufacturers can achieve additional reductions with more lead time, questions pertaining to applicability of advanced technologies that existed at that time, and the hope of future pursuit of more stringent international standards. The anticipated creators of the more stringent Tier 2 standards were to further assess changes in technology and consider application to engines on foreign vessels entering U.S. ports by an April 27, 2007 deadline.

Interestingly, when the April 27, 2007 deadline arrived for the EPA to promulgate a new Tier of emission standards for Category 3 engines, the EPA decided instead to propose a new deadline of December 17, 2009. The EPA published this decision as a direct and final rule because it did not anticipate adverse comments on what they saw as a noncontroversial issue.

However, in September 2007, Friends of the Earth filed a Complaint for Declaratory and Injunctive Relief against the EPA. In the complaint, Friends of the Earth argued that the EPA had violated § 213(a)(3) of the Clean Air Act by failing to meet its deadline and also violated the Administrative Procedure Act by failing to fulfil the non-discretionary duty to create a new Tier of Category 3 standards. The EPA responded to the environmental group's complaint by supporting standards as reflected in its proposal to the IMO for new Annex VI rulemaking.[8]

The EPA is "considering standards for achieving large reductions in NOx and particulate matter (PM) through the use of technologies such as in-cylinder controls, aftertreatment, and low sulfur fuel, starting as early as 2011."73 The proposed standards consist of two Tiers for NOx emissions and new performance-based SOx standards that reflect technology improvements and expectations. The standards consist of:[8]

- New Particulate Matter and SOx limits applying in 2011/2012 to all ships operating in specific areas defined under the treaty.

- Tier 2 NOx limits for new Category 3 propulsion engines beginning in 2011 (to achieve a 15% to 25% NOx reduction).

- Tier 3 NOx limits for new Category 3 propulsion engines beginning in 2016 applying when ships operate in the Particulate Matter/SOx geographic areas

requiring the use of high-efficiency catalytic aftertreatment emission control technology (to achieve NOx reductions of more than 80%).

- NOx limits for engines built before Jan. 1, 2000 that would achieve a 20% NOx reduction to phase-in beginning 2010/2012. [8]

4.5 Other Limits

Other emissions limits applied outside *MARPOL* include [9]:

- 2010 fuel sulphur 0.1% at berth in European Union;

- 2009 distillate fuel, fuel sulphur 1.5%/0.5% depending on fuel aromaticity, in Californian waters;

- 2012 distillate fuel, fuel sulphur 0.1%, in Californian waters.

4.6 Emissions at berth (Hotelling)

Ports are frequently close to urban areas. Diesel generators on ships are used to make electricity for hotelling loads, cargo handling, and ballast pumping. Oil fired boilers are used to heat fuel or cargo, make steam for steam driven cargo pumps and to make hot water. Cruise ships have high hotelling loads providing air conditioning, lighting, refrigeration, cooking, etc. Two measures being implemented to reduce emissions at berth are [9]:

- Fuel switching, currently involving use of low sulphur fuel while at berth, will reduce SOx and PM emissions. The future may also see ship generators designed to run on LNG at berth to further reduce SOx and PM emissions and also reduce NOx.

- Shore power (alternative maritime power, cold ironing). Ship electricity is supplied from the land grid. This shifts air quality emissions away from the port. The net gain depends on the shore power source. Diesel engines are generally more efficient than the existing large scale electricity generating facilities operating on coal or natural gas, so the use of shore power can result in a net increase in greenhouse gases. However, diesel engines produce more NOx and particulate matter. The use of shore power for ship electricity doesn't replace the on-board boilers so the SOx reduction from the use of shore power is not

necessarily as big as for fuel switching. Some ports are implementing LNG powered auxiliary generators at the port to provide ship electricity.

4.7 Natural gas

Natural gas is composed primarily of methane and contains virtually no sulphur. Engines running on natural gas produce less than 20% of the NOx and PM from diesel engines on liquid fuel. SOx emissions are negligible.

Dual fuel diesel engines use natural gas as the main fuel source with a small amount of diesel fuel injected to initiate the combustion. They can run with 80% to 99% of fuel energy from gas. They are particularly suitable for marine usage because they can revert to 100% liquid fuel operation immediately if the gas supply fails, providing a high degree of propulsion reliability for ship safety.

The engine technology is well developed and a range of duel fuel engines are available from the major engine manufacturers. Gas only engines are also available and will be used in multi-engine arrangements.

The use of natural gas can also result in 25% greenhouse gas reduction if the combustion system is well designed, so that there are no significant emissions of methane. The emissions from gas engines can meet the most stringent IMO NOx and SOx emissions limits (IMO Tier 3 in ECAs) without aftertreatment. Particulate emissions are very low compared with liquid fuelled diesel engines.

Liquefied Natural Gas (LNG) allows greater fuel quantities in a given space than compressed natural gas. The gas is stored as a very cold liquid in highly insulated tanks at moderate pressures. The technology for storage and safe handling is well developed.[9]

4.8 Greenhouse Gas Emissions

Shipping produces around 15% of global transport CO_2 emissions, while shipping performs around 70% of the global freight task. The mass of CO_2 emitted per tonne-km for shipping is around 30% of road transport, making shipping an attractive option for reducing greenhouse gas emissions. Ship CO_2 emissions are compared with rail, road transport (trucks) and aviation in Figure 3.

CO_2 is the main greenhouse gas emitted by ships. Methane (CH_4) and nitrous oxide (N_2O) emissions from ship engines have a minor global warming role compared with CO_2. Further, SOx, NOx, PM and VOC also have a minor role in global warming. Particulate matter arising from SOx emissions has a potential cooling effect and/or creates local climate disturbance. The sulphur content of marine fuels will decrease due to IMO MARPOL Annex VI and other measures.

There are interaction between greenhouse gas mitigation measures and air quality mitigation measures. For instance, reducing NOx emissions can increase fuel consumption and thus increase CO_2 emissions. [9]
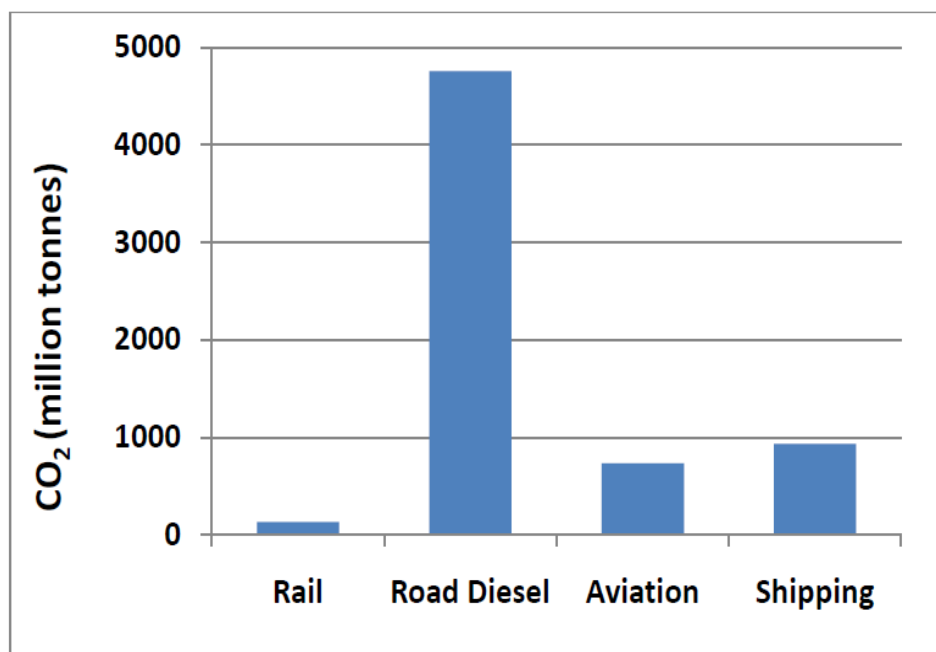

Figure 3. 2005 Global Transport CO_2 emissions (IMO2009-excludes automobiles-goods transport only. Data taken from 2nd IMO greenhouse gas study 2009. [9]

5 FLEET-GENERATED POLLUTANT EMISSIONS

5.1 General information

In this chapter, the fleet is divided into small, medium, and large ships according to the installed auxiliary engine (AE) and main engine (ME) power.

For this study it was assumed that vessels which visit a port at least every eight weeks are on regular service. This is a working assumption purely for the purposes of this study, as the above mentioned databases used in this study do not enable a direct identification of such vessels based on the definition in the Sulphur Content of Marine Fuels Directive.[10]

The specific costs and emission reductions per representative ship in each size category are then scaled up to provide an estimate of the cost of installing and using emission abatement technologies on all the engines onboard ships. The focus of this quantification is on EU flagged vessels.

In the following sections the general assumptions used in the study are described in detail. [10]

5.2 Number of engines per ship

Emission abatement equipment is often fitted on an engine-by-engine basis. Therefore the costs of emission abatement equipment will vary depending upon the size and number of engines. This study assumes that there are 1 ME and 4 AEs installed per ship as depicted in Table 4 [10].

Table 4. Assumed engine numbers and engine sizes for three different vessel size classes [10]

	Small	Medium	Large
ME	1 small	1 medium	1 large
AE	4 small	4 medium	4 large

5.3 Engine sizes

5.3.1 Main engine size

Three main engine size categories were chosen to represent the range of engine sizes in the EU-flagged fleet. Within each category a rough estimate of a representative size was chosen, as shown in Table 5. This table also illustrates the range of engine sizes in each category and the profile for the world and EU-flagged fleet [10].

Table 5. Main engine size categories and representative engine size [10]

	Small	Medium	Large
Class boundaries ME kW rating (kW)	ME < 6,000kW	6,000kW <= ME < 15,000kW	15,000kW =< ME
Upper and low engine sizes in each range (kW)	75 – 6,000	6,000 – 15,000	15,000 – 146,618
Representative engine size used in calculations (kW)	3,000	10,000	25,000
Fraction of ships using SSD 2-stroke engines	48%	58%	55%
EU-flagged fleet > 500GT			
Fraction of EU-flagged ships falling into the ME categories	55%	35%	10%
Fraction of total EU-flagged fleet installed capacity	20%	45%	35%
World fleet > 500GT			
Fraction of world fleet ships falling into the ME categories	60%	30%	10%

5.3.2 Auxiliary engine size

Three auxiliary engine size categories were chosen to represent the range of installed AE capacity in the EU-flagged fleet. Within each category a representative installed capacity was chosen as depicted in Table 6. This table also illustrates the range of engines sizes in each category and the profile for EU-flagged fleet.

Table 6. Auxiliary engine size categories and representative engine size [10]

	Small	**Medium**	**Large**
Class boundaries AE kW rating (kW)	AE < 1,000kW	1,000kW <= AE < 2,000kW	2,000kW =< AE
Representative installed engine capacity used in calculations (kW)	530	1,470	3,780
Upper and low engine capacity in each range (kW)	4 - 1,000	1,000 – 2,000	2,000 – 18,687
Fraction of EU-flagged ships falling into the AE categories	33%	33%	33%
Fraction of total EU-flagged fleet installed AE capacity	10%	25%	65%

The proportion of installed engine capacity represented by MEs and AEs is shown in Table 7. This outlines the dominant contribution which installed ME capacity makes to total installed capacity aboard ships.[10]

Table 7. Proportion of installed capacity represented by MEs and AEs [10]

	Small	**Medium**	**Large**
Fraction of ME installed capacity of total ship's installed capacity (%)	84%	88%	91%
Fraction of AE installed capacity of total ship's installed capacity (%)	16%	12%	9%
Total installed capacity (%)	100%	100%	100%

5.4 Engine load factors

Table 8 outlines the assumed engine load factors of MEs and AEs for ships at sea, at berth and maneuvering. Load factors will vary between ship types but for the purposes of this study average load factors are used.[10]

Table 8. Main and auxiliary engine load factors (note1: This assumption underestimates the emissions for tankers at berth since tankers operate MEs at higher operating times) [10]

	ME		**AE**	
	Load factor (%)	Operation (% of time)	Load factor (%)	Operation (% of time)
At sea	80%	100%	30%	100%
Ships at berth	20%	5% (Note 1)	40%	100%
Manoeuvring	20%	100%	50%	100%

5.5 Operating hours

Table 9 outlines the average operating times at sea and in port (maneuvering and at berth)[10]

Table 9. Assumed average operating hours for different activities and locations [10]

	Average operating hours of engines (hours/year)
Time at Sea	6,000
Time at Berth	700
Time Manoeuvring	20
Total Operation Time	6,720
Not Operating (no relevant load factors on engines) (refurbishment etc)	2,040
Total hours per year	8,760

5.6 Total engine use

Total power used by engines per year was calculated by multiplying the representative installed capacity for each engine size category (Table 5, Table 6) by the engine loads (Table 8) and hours of operation (Table 9). Table 10 and Table 11 show the yearly power consumption by main and auxiliary engines in the different modes per year. Table 12 depicts the total power used in the different modes per ship of a certain size.[10]

Table 10. Main engine power use per vessel and year [10]

	Small (kWh/year)	**Medium (kWh/year)**	**Large (kWh/year)**
At sea	14,400,000	48,000,000	120,000,000
At berth	21,000	70,000	175,000
Manoeuvring	12,000	40,000	100,000
Total Power Use	**14,433,000**	**48,110,000**	**120,275,000**

Table 11. Auxiliary engine power use per vessel and year (there are 4 AEs per ship)[10]

	Small (kWh/year)	**Medium (kWh/year)**	**Large (kWh/year)**
At sea	4 X 252,000 = 1,008,000	4 X 666,000 = 2,664,000	4 X 1,710,000 = 6,840,000
At berth	4 X 39,200 = 156,800	4 X 103,600 = 414,400	4 X 266,000 = 1,064,000
Manoeuvring	4 x 1,400 = 5,600	4 x 3,700 = 14,800	4 x 9,500 = 38,000
Total Power Use	**4 x 292,600 = 1,170,400**	**4 x 773,300 = 3,093,200**	**4 x 1,985,500 = 7,942,000**

Table 12. Total engine power use per vessel (1 ME and 4 AEs) [10]

	Small (kWh/year)	Medium (kWh/year)	Large (kWh/year)
At sea	15,408,000	50,664,000	126,840,000
At berth	177,800	484,400	1,239,000
Manoeuvring	17,600	54,800	138,000
Total Power Use	**15,603,400**	**51,203,200**	**128,217,000**

5.7 Fuel consumption

Specific fuel consumption factors used are outlined in Table 13. Expected average fuel use per year by auxiliary engines at berth is outlined in Table 14, and is used specifically in the report on shore-side electricity. The total fuel consumption of the different vessel sizes are depicted in Table 15 [10]

Table 13. Specific fuel consumption [10]

	sfc (g/kWh)
Shore-side Electricity Report – Auxiliary engines using 0.1% sulphur MD	217
Shore-side Electricity Report – Auxiliary engines using 2.7% sulphur RO	227
Nox Abatement and Sea Water Scrubbing Reports – Both main and auxiliary engines using a mix of RO and MD	200
NOx Abatement and Sea Water Scrubbing Reports – Ships using MD	196

Table 14. Fuel consumption by AEs at berth per vessel and year [10]

	Small (t/year/vessel)	Medium (t/year/vessel)	Large (t/year/vessel)
Fuel consumption by AEs at berth	32	89	230

Table 15. Total fuel consumption per vessel and year [10]

	Small (t/year)	Medium (t/year)	Large (t/year)
At sea	**3,082**	**10,133**	**25,638**
At berth	**40**	**110**	**281**
Manoeuvring	**4**	**12**	**31**
Total fuel consumption per year	**3,126**	**10,255**	**25,680**

5.8 Approach to emissions estimations

5.8.1 Emission factors

Emission factors assumed for this task are shown in Table 16. These figures are average figures based on emission factors for individual engine types, load factors and engine type composition of world fleet. As these figures are averages there can be significant variation across individual ships and situations .

Table 16. Emission factors (Note 1: PM is total primary particulate matter. The dominant particle size for diesel engines can be expected to be <1 micrometer) [10]

Emission factor	NO_x (g/KWh)	SO_2 (g/KWh)	VOC (g/KWh)	PM (g/KWh)
Shore-side Electricity Report-Auxiliary engines using 2.7% sulphur RO (current average)	12.47	12.30	0.40	0.80
Shore-side Electricity Report-Auxiliary engines using 0.1% sulphur MD (EU 2010 limit)	11.8	0.46	0.40	0.30
NO_X Abatement and Sea Water Scrubbing Reports-Both main and auxiliary engines using a mix of RO and MD	15.0	11.0	0.55	1.2

The use of shore-side electricity will be compared to ships using 2.7% sulphur residual oil, the current mix of fuels used at berth. The use of shore-side electricity will also be compared to 0.1% sulphur marine distillate (MD) at berth – as 0.1% will be the sulphur limit for ships at berth in EU ports from 2010, under the recently agreed marine fuel sulphur directive.

An average figure for NOx of 15 gNOx/kWh was used for engines at sea. This was to reflect the likely emissions in 2010 to take into account the slight drop in NOx emissions from the current average 16 gNOx/kWh due to the IMO NOx code implemented for engines built after 2000. [10]

5.8.2 Emissions produced at berth by Auxilary Enginers

The expected emissions produced at berth by auxiliary engines are shown in Table 17. It was assumed that a berth that provides shore-side electricity has an average utilization of 70% (i.e. 6,132 hours/year) of the time and serves only ships of a certain size (small, medium, or large). The emissions are shown as the amount produced at a particular berth per year, which refers to the emissions from all the engines on all the ships that visit that berth that year [10].

Table 17. Total annual emissions produced by AEs at one berth [10]

Emission	Small	Medium	Large
AEs using 2.7% sulphur RO	(t/year/berth)	(t/year/berth)	(t/year/berth)
NO_X	16.2	44.9	115.7
SO_2	16.0	44.3	114.1
VOC	0.5	1.4	3.7
PM	1.0	2.9	7.4
AEs using 0.1% sulphur MD			
NO_X	15.3	42.4	109.1
SO_2	0.6	1.7	4.4
VOC	0.5	1.4	3.7
PM	0.4	1.1	2.8

5.8.3 NOx and SO_2 emissions produced by all engines in all operations

Table 18 and Table 19 outline the NOx and SO_2 emissions produced by both main and auxiliary engines in all operating modes: at sea, maneuvering and at berth. This is based on the fuel mix used by engines in the year 2000, prior to regulations requiring all ships at berth to use 0.1% sulphur marine distillate [10].

Table 18. NOx emissions produced per vessel and year [10]

NO_x	Small	Medium	Large
	(t/year/vessel)	(t/year/vessel)	(t/year/vessel)
At sea	231	760	1903
At berth	3	7	19
Manoeuvring	0	1	2
Total Emissions	234	768	1924

Table 19. SO2 emissions produced per vessel and year [10]

SO_2	Small	Medium	Large
	(t/year/vessel)	(t/year/vessel)	(t/year/vessel)
At sea	169	557	1395
At berth	2	5	14
Manoeuvring	0	1	2
Total Emissions	171	563	1411

6 EMISSION REDUCTION TECHNOLOGIES

6.1 General information

A diesel engine is a type of internal-combustion engine in which atomized oil fuel is sprayed into the cylinder and ignited by the heat generated by compression. Diesel engines are efficient with low carbon dioxide, carbon monoxide and hydrocarbon emissions. However the emissions are high in nitrogen oxides. Additionally marine engines use residual bunker fuels which contain sulphur, asphaltenes and ash. Due to these components in the fuel, exhaust emissions contain oxides of sulphur and particulate matter which are formed during the combustion process.

Typical concentrations of exhaust emissions are as follows [11]:

- Oxygen: abt. 13%,

- Oxides of Sulphur (SO_X): abt. 600 ppm

- Nitrogen: abt. 75.8%,

- Carbon Monoxide (CO): abt. 60 ppm

- Carbon di Oxide (CO_2): abt. 5.2%,

- Hydrocarbons (HC): abt. 180 ppm

- Water vapor: abt. *5.35%*,

- Particulate matter (PM): abt. 120 mg/Nm^3

- Oxides of Nitrogen (NO_X): abt. 1500 ppm.

Fuel is injected at high pressure (through fuel injectors which atomize the fuel) into the combustion chamber towards the end of the compression stroke. The fuel ignites, thereby increasing the pressure in the combustion chamber and pushes the piston downward on the power stroke. When the fuel ignites, the flame front travels rapidly into the combustion space and uses the compressed air to sustain the ignition. Temperatures at the envelope of the flame can exceed 1300°C, although the mean bulk temperatures in the combustion chamber are much lower [11].
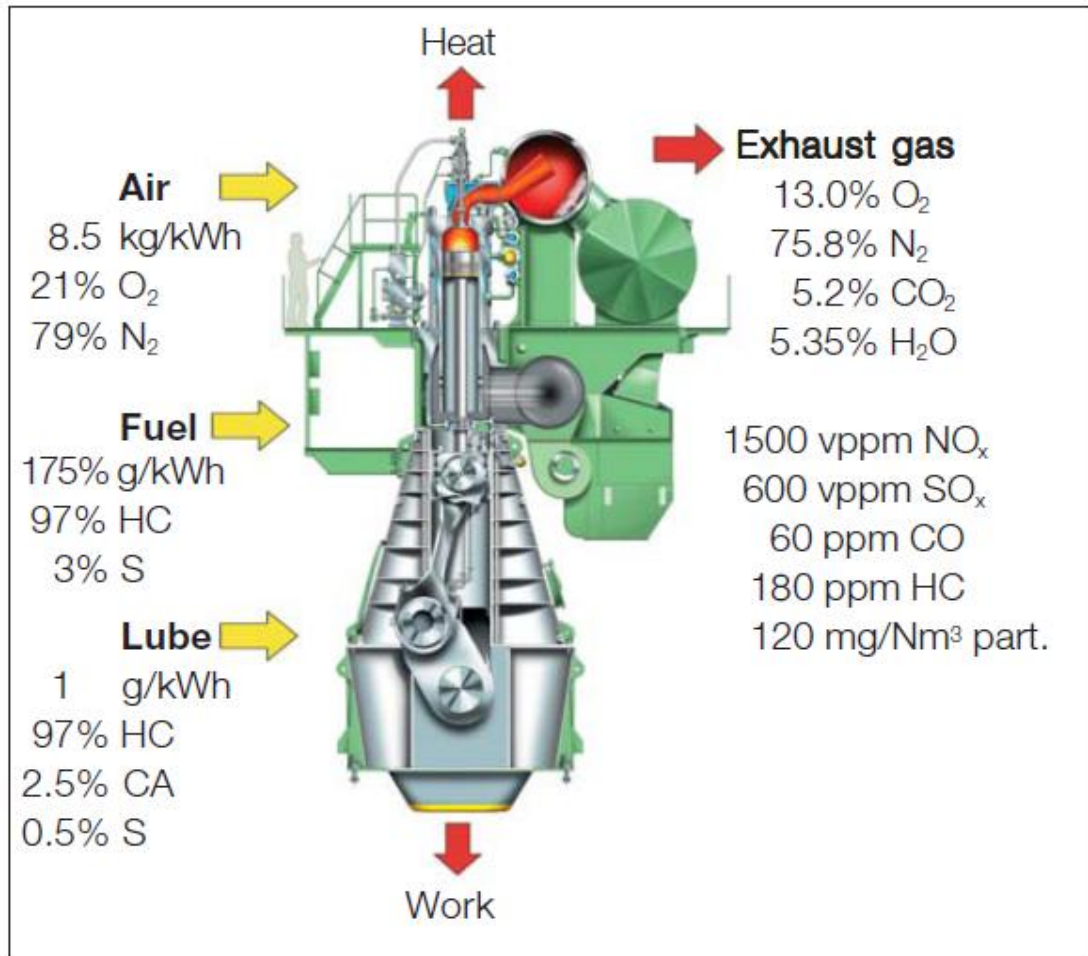
Figure 4. Flow process and typical exhaust gas composition [12]

6.2 NOx Abatement techniques

This chapter investigates the costs, emissions reductions and cost effectiveness of specific NOx reduction measures on ships. The following measures are investigated [11]:

A. Primary methods (i.e. Internal Measures)

- Dry methods

  - Internal Engine Modifications (IEM);

  - Exhaust Gas Recirculation (EGR);

- Wet methods

  - Direct Water Injection (DWI);

  - Inlet Air Humidification

- Water fuel emulsion

B. Secondary methods (i.e. External Measures)

- Selective Catalytic Reduction (SCR).
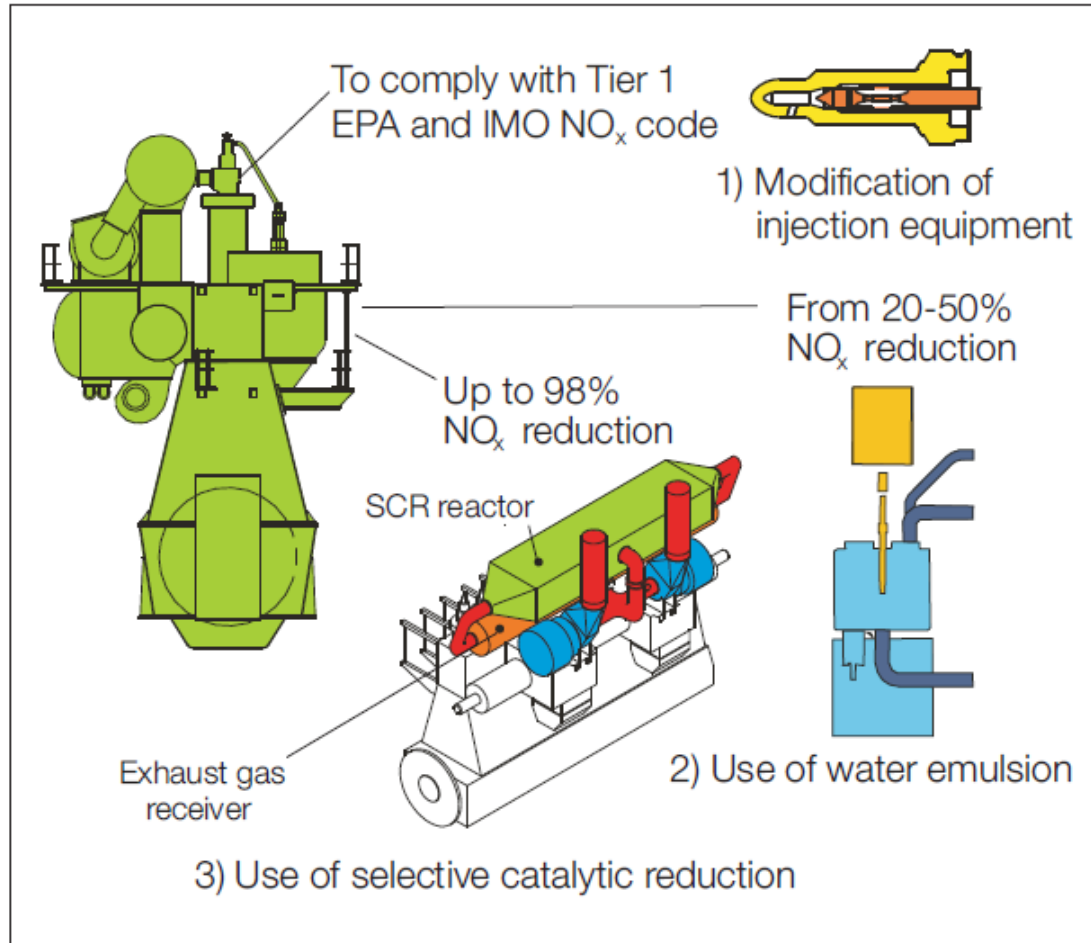
Figure 5. NO_X reduction methods [12]

6.3 Internal Engine Modifications (IEM)

There is a large range of methods by which engines can be modified to reduce NOx emissions. These methods aim to either optimize combustion, improve air charge characteristics or alter the fuel injection system. Research and development is required to determine the correct combination of modifications appropriate for each engine type. This paragraph describe the large range of IEMs available with two categories:

- 'Basic IEM' (slide valves); and

- 'Advanced IEM'.

6.3.1 Basic Internal Engine Modifications

The most widespread internal engine modifications (IEMs) is the exchange of conventional fuel valves with low-NOx fuel valves of the sliding type. This measure is only applicable for slow-speed 2-stroke engines. Virtually all new slow speed 2 stroke engines delivered after 2000 have these valves fitted as standard, as a means of meeting the IMO NOx standard.[13]

Slide valves are designed to optimise spray distribution in the combustion chamber without compromising on component temperatures and thereby engine reliability.

The main purpose of these valves was initially to reduce fouling at the piston top, exhaust channels and exhaust boiler. With a conventional fuel injector, the air swirl and the fuel vapour pressure during the scavenging interval will blow out a part of the fuel from the so-called sac volume. This fuel enters the combustion zone when the temperature is too low for a complete combustion to occur which results in engine fouling and increased soot and VOC emissions.

Heat release with slide valves is somewhat lower than conventional fuel injectors, which means they also result in a beneficial NOx reduction. This can be enhanced further by special low-NOx atomisers on the valve where the spray pattern is optimised for reducing NOx by around 20% and even lower in special cases. The actual NOx emission performance level for individual engine types is normally tested in the laboratory in advance.

Slide valves may provide considerable reductions in VOC and PM emissions [13]. Tests have shown that the main source of smoke and soot deposits is the fuel trapped into the fuel injector sac hole, which enters the combustion chamber in an uncontrolled way during the expansion stroke.

The assumed NO_x reduction efficiency of slide valves is shown in Table 20

Table 20. NOX reduction efficiency of slide valves and impact on other emissions quoted by manufactures [13]

In-engine changes	NO_x	SFC	PM	VOC	CO
Slide valves	-20%	0%	Unconfirmed up to -50% dependent upon fuel type	Unconfirmed up to -50% dependent upon fuel type	Some increases possible
Reduction efficiency assumed in this study	-20%	0%	0%	0%	0%

Retrofit installations are easy to undertake. The retrofit only entails removing the old valves, and enlarging the fuel injector holes in the cylinder covers. It is usually possible to enlarge the hole with the cover still in position i.e. by removing just the exhaust valve. In addition, some engines may require stronger spring housings for securing the fuel valves to the cylinder cover.

Changes are normally made on all cylinders simultaneously, and consequently installation can take a few hours work by the ship' s crew per cylinder, totalling around a day per engine, and not requiring the ship to be in dry dock.

Retrofitting of slide valves has been developed for some 2 stroke engines. Such engines include, for example, the motor series C type ('MC type') engine family produced by the 2 stroke engine manufacturer, MAN B&W. MAN B&W have proprietary technology for slide values and claim a market share of over 50 percent on slow speed diesels during the last years.

Retrofitting of slide valves is likely to be technically possible for all 2 stroke engines, but development work is required to fully test the application of slide valves to these engines. Since the MC type represents engines younger than 15 years produced by MAN B&W, it is assumed that young engines (less than 15 years old) can be immediately retrofitted with slide valves without development costs. [13]

6.3.2   Advanced Internal Engine Modifications

Optimized combinations of a number of internal engine modifications developed for particular engine families are referred to in this chapter as 'Advanced IEM'. For this technique, it is important to note that the NOx reductions quoted are targets which the manufacturers have set, and that advanced IEMs for ships are generally still in the development phase. Examples of particular techniques include [11]:

- **Retard injection/Miller cycle valve timing.**

- **Higher compression ratio/Adjustable compression.**

- **Increased turbo efficiency/Two stage turbocharger.**

- **Common rail injection/Flexible injection system/Two stage injection.**

- **Higher cylinder pressure.**

- **Low intake temperature.**

Specific combinations of IEMs which are being developed by manufacturers can be seen in Table 21.This table shows the NOX reduction efficiency. It is important to note that the NO_X reductions quoted are targets which the manufacturer has set, and that advanced IEMs are still in the development phase. The costs for IEM represented in this study include research and development costs still required by manufacturers. The research and development costs included are enough to allow for exploration beyond fuel injection modifications.

Since the available cost data is for IEM combinations which reduce NO_X emissions by 30% below the IMO NO_X standard , the NO_X reduction efficiency is assumed at 30% below the IMO NO_X standard.

Table 21. Combinations of advanced internal engine modifications, NOX reduction efficiency and impact on other emissions [13]

Manufacturer	In-engine changes	NO_x	sfc	PM	VOC	CO
Wartsila	Retard injection,Miller cycle valve timing, Higher compression ratio, Increased turbo efficiency, higher max cylinder pressure, common rail injection	-40% below IMO NO_x standard	unknown	unknown	unknown	unknown
Caterpillar (MaK)	Higher compression ratio, Higher cylinder pressure, Higher charge pressure, Flexible injection system	-33% below IMO NO_x standard	0%	unknown	unknown	unknown
FMC	Two stage injection, Miller cycle valve timing, Greater stroke/bore ratio, Adjustable compression, two stage turbocharger, low intake temperature	-34% below IMO NO_x standard	-2%	unknown	unknown	unknown

6.3.2.1 *Injection timing retard*

NOx formation depends on temperature as well as residence time. The burnt gas arising from the part of the combustion which occurs before peak pressure is compressed due to the rising pressure in the combustion chamber. This means it remains at high temperatures for a long time compared with the burnt gas from the later stages of combustion. This allows more time for NOx to form. Delayed injection leads to lower pressure and temperature throughout most of the combustion. Delayed injection increases fuel consumption due to later burning, as less of the combustion energy release is subject to the full expansion process and gas temperatures remain high later into the expansion stroke, resulting in more heat losses to the walls. Smoke

also increases due to reduced combustion temperatures and thus less oxidation of the soot produced earlier in the combustion.[14]

6.3.2.2 *Miller Timing*

In the Miller cycle, the intake valve is left open longer than it would be in an Otto cycle engine. In effect, the compression stroke is two discrete cycles: the initial portion when the intake valve is open and final portion when the intake valve is closed. This two-stage intake stroke creates the so called "fifth" stroke that the Miller cycle introduces. As the piston initially moves upwards in what is traditionally the compression stroke, the charge is partially expelled back out the still-open intake valve. Typically this loss of charge air would result in a loss of power. However, in the Miller cycle, this is compensated for by the use of a supercharger. The supercharger typically will need to be of the positive displacement (Roots or Screw) type due to its ability to produce boost at relatively low engine speeds. Otherwise, low-rpm torque will suffer.

A key aspect of the Miller cycle is that the compression stroke actually starts only after the piston has pushed out this "extra" charge and the intake valve closes. This happens at around 20% to 30% into the compression stroke. In other words, the actual compression occurs in the latter 70% to 80% of the compression stroke.

In a typical spark ignition engine, the Miller cycle yields an additional benefit. The intake air is first compressed by the supercharger and then cooled by an intercooler. This lower intake charge temperature, combined with the lower compression of the intake stroke, yields a lower final charge temperature than would be obtained by simply increasing the compression of the piston. This allows ignition timing to be advanced beyond what is normally allowed before the onset of detonation, thus increasing the overall efficiency still further.

An additional advantage of the lower final charge temperature is that the emission of NOx in diesel engines is decreased, which is an important design parameter in large diesel engines on board ships and power plants.

Efficiency is increased by raising the compression ratio. In a typical gasoline engine, the compression ratio is limited due to self-ignition (detonation) of the compressed, and therefore hot, air/fuel mixture. Due to the reduced compression stroke of a Miller cycle engine, a higher overall cylinder pressure (supercharger pressure plus

mechanical compression) is possible, and therefore a Miller cycle engine has better efficiency.

The benefits of utilizing positive displacement superchargers come with a cost. 15% to 20% of the power generated by a supercharged engine is usually required to do the work of driving the supercharger, which compresses the intake charge (also known as boost).

A similar delayed-valve closing method is used in some modern versions of Atkinson cycle engines, but without the supercharging. These engines are generally found on hybrid electric vehicles, where efficiency is the goal, and the power lost compared to the Miller cycle is made up through the use of electric motors.

Principles of functioning [15]:

1. Miller closes before BDC
2. Expansion aspirated air
3. Lower temperature
4. Lower NOx level
5. Lower fuel consumption
6. In part load thermal load high
7. Smoke.
8. Variable Inlet Closing (VIC)
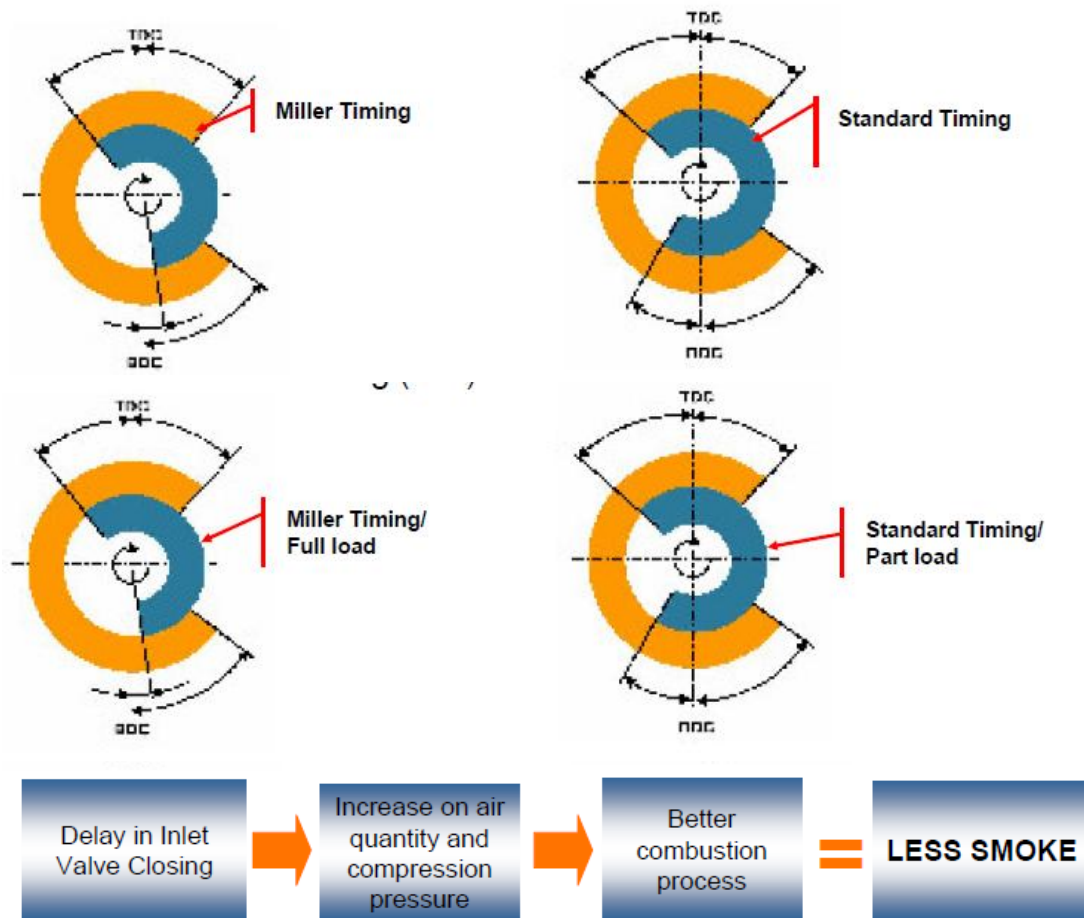
Figure 6. Miller timing-principles of functioning [15]

6.3.2.3 *Higher compression ratio/Adjustable compression, injection timing and injection rate*

The most common engine tuning measure is increased compression ratio combined with retarded injection timing. Figure 7 shows the combination of increased compression ratio and delayed injection timing for a slow speed engine. The peak pressure is the same as for the standard engine and occurs at about the same crank angle, even though combustion begins later than for the standard engine. This means that there is less after-compression of the earlier burnt gas, so it does not reach as high

a temperature as in the standard case and it resides at high temperature for less time. Increased compression ratio also tends to offset the increases in fuel consumption resulting from retarded injection timing.
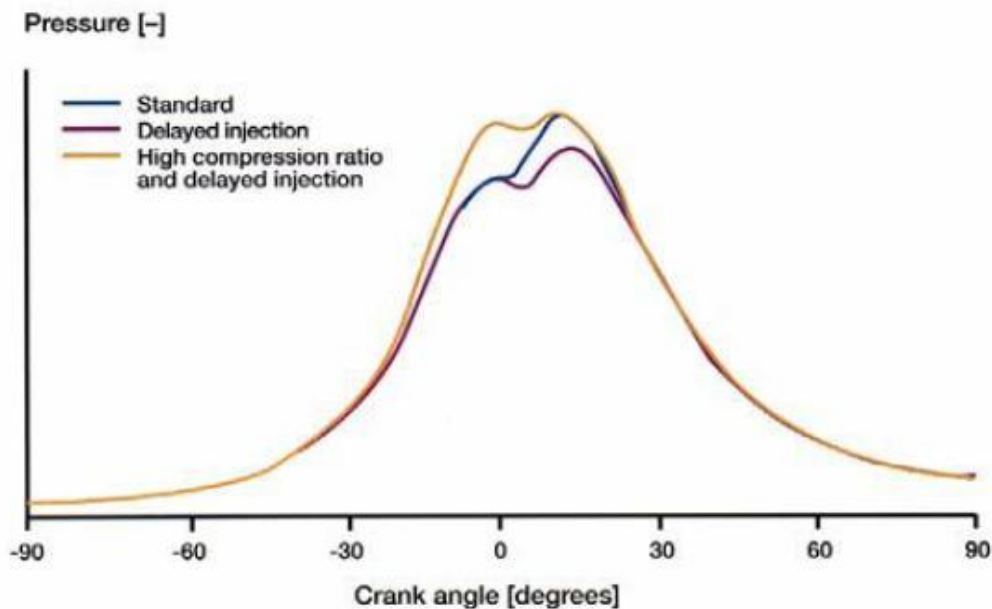
Figure 7. Cylinder pressures for a sulzer RTA engine with standard compression ratio,delayed injection, and delayed injection combined with increased compression ratio [14]

For a medium speed engine, increasing the compression ratio from 15.5 to 17 while retarding injection timing to limit the increase in peak cylinder pressure to about 20 bar (from 180 bar), gave NOx reduction from about 12 g/kWh to about 8 g/kWh, without increasing fuel consumption.

For a slow speed engine, the maximum NOx reduction achievable with increased compression ratio and retarded timing is 25% with about 1% fuel consumption penalty. The compression ratio can be increased by increasing geometric compression ratio or advancing exhaust valve closing. Advancing exhaust valve timing would increase the charge mass. This would increase the amount of mass available to absorb the combustion energy but would also increase the amount of oxygen available for NOx production.

Iincrease of the scavenge air pressure together with retarded injection timing may increase or decrease NOx, depending on the engine design. If the geometric compression ratio is increased by reducing the clearance volume, the combustion space will be flatter, which could result in more cooling of the flame by the surfaces and thus increased soot with an additional decrease in NOx due to the cooling.

Combustion chamber shape and fuel spray geometry may need to be adjusted to compensate for reduced combustion chamber height.

For 4 stroke medium speed engines, very high compression ratio may require reduced valve overlap to avoid contact between the valves and the pistons. This reduces scavenging efficiency and cooling of the exhaust valve. Reduced scavenging efficiency can lead to reduced NOx.

Wartsila reported a NOx lowering conversion for the Vasa 32 medium speed diesel in 1999 [14]. The conversion aims for the ideal combination of compression ratio, injection timing and injection rate. By increasing compression ratio and increasing combustion pressure while retarding fuel injection and increasing injection rate, they reduce NOx from 15 g/kWh to 10-11.5 g/kWh and reduce fuel consumption by up to 4%. The conversion requires a new piston, designed to withstand the higher pressures, and modified fuel injection equipment.

Vestergren [14] reports that the implementation of "Low NOx combustion" on Wartsila medium speed and high speed engines has reduced NOx by between 25% and 35% with unaffected or slightly improved fuel consumption. This involves retarded injection timing, increased compression ratio, optimised combustion chamber optimised fuel injection and early inlet valve closing. Optimised combustion chamber and fuel injection have kept smoke non-visible despite the increased compression ratio.

Mitsubishi states that all UEC engines meet Marpol Annex VI NOx levels by engine fine tuning (injection timing retard, low NOx fuel injection valve, etc)[14].

MTU has described its NOx control measures on the new MTU Series 8000 (1150 RPM, 450 kW per cylinder)[14]. They use injection timing retard, increased compression ratio, and optimised injection. The optimised injection improves mixing and reduces soot generation by optimising number of nozzle holes, hole shape and spray angle.

Electronically controlled common rail fuel injection allows optimisation of the engine for NOx and fuel consumption. The combustion chamber shape was also optimised.

MAN B&W have used increased compression ratio in combination with retarded injection timing in their slow speed engines, but not to the extent used by Sulzer. They contend that the fuel consumption penalty from retarded injection timing is too

great. Optimised fuel injection and nozzle design have been their main strategy for reaching IMO levels.

A MAN B&W 48/60 medium speed diesel (514RPM), when strictly optimised for lowest fuel consumption, has a typical NOx emission of about 16g/kWh. When optimised for low NOx using engine tuning, it yields about 12g/kWh NOx. (With fuel water emulsions at 15% water to fuel, the NOx output comes down to about 7-8 g/kWh)[14]

Yanmar Diesel used increased compression ratio, retarded injection timing and shortened injection duration to reduce NOx from their medium speed auxiliary engines to Marpol Annex VI levels, with a 10 g/kWh reduction in fuel consumption[14]. They employed intake induced swirl and a deep bowl combustion chamber which induced squish, to enhance the combustion rate by enhanced mixing. An increased number of injection nozzle holes and smaller nozzle holes gave good fuel distribution through the deep bowl combustion chamber. This arrangement gave low smoke at low loads, without the need for common rail injection[14].

6.3.2.4   *Increased turbo efficiency/Two stage turbocharger*

Today for ship propulsion, we have two main engine types with the typical ranges of parameters which is based on the data for engines in the Wartsila marine programme. The examples of large two-stroke engines are taken from the Sulzer RTA series[15]. The engines are all uniflow scavenged with air entering the cylinder through ports around the full circumference of the liner at the bottom of the piston stroke, and exhaust from a single poppet-type valve in the centre of the cylinder cover. Sulzer two-stroke engines have been uniflow scavenged since 1982.

The turbochargers operate on a constant pressure system, with scavenge air pressures up to 3.9 bar. There are one to four turbochargers, all located high on the side of the engine, outboard and beneath the exhaust manifold. This allows an efficient arrangement with the scavenge air cooler and its associated water separator unit located immediately below the turbocharger and adjacent to the scavenge air space on the piston underside.
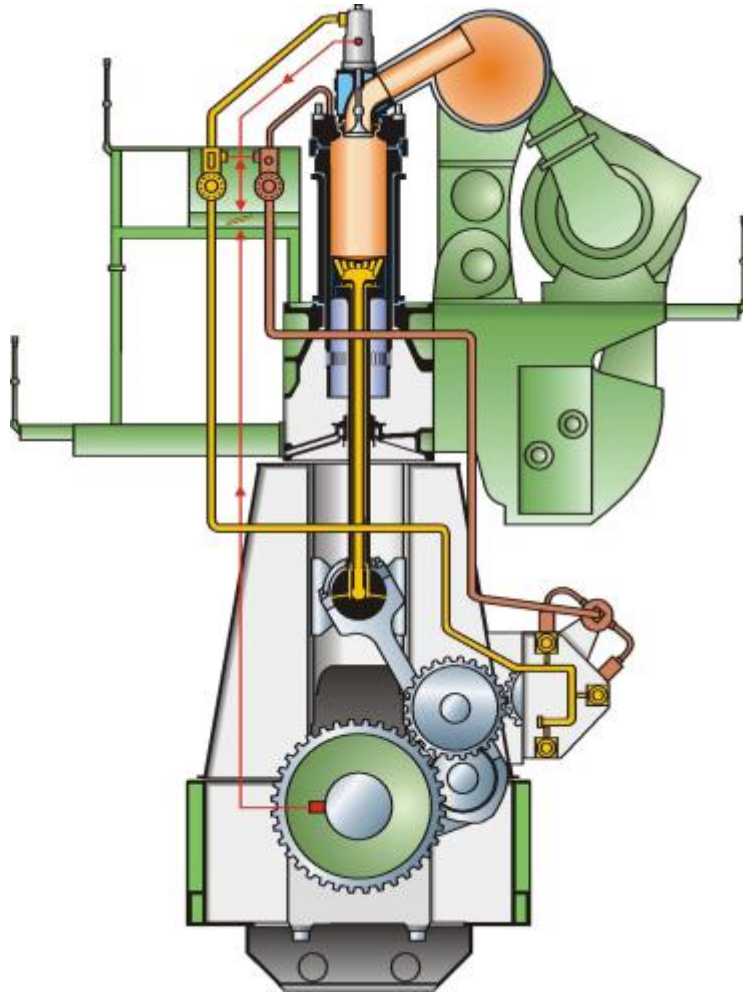
Figure 8. Cross section of a modern two-stroke diesel engine [16]
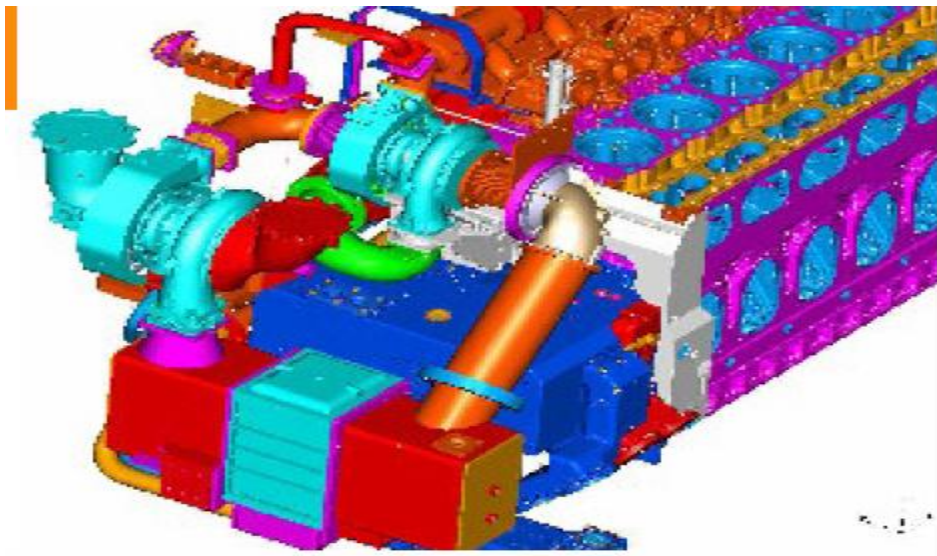
Figure 9. NOx reduction methods 2-stage turbo [16]
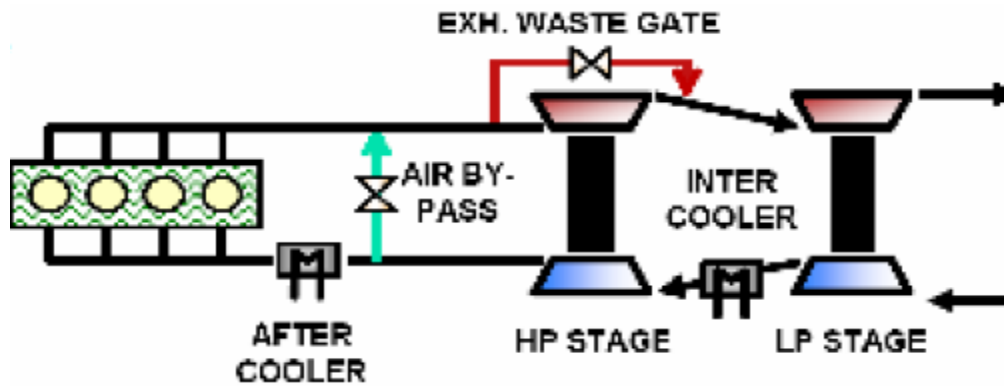
Figure 10. NOx reduction methods 2-stage turbo[16]

6.3.2.5 *Common rail injection/Flexible injection system/Two stage injection*

There are benefits by common rail injection. These are:

- Environmental

- Operational and economical

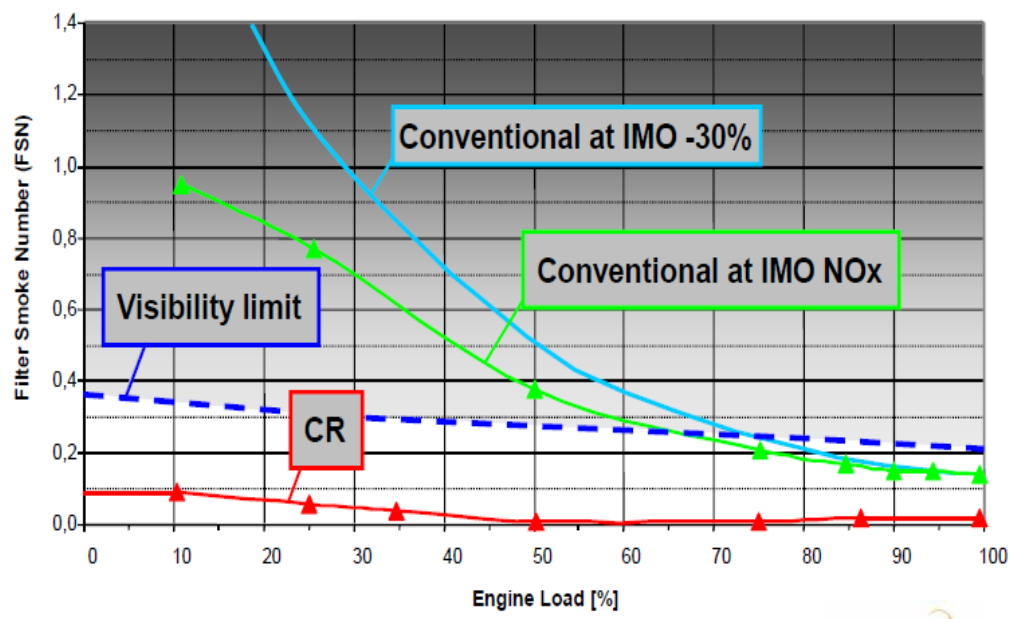One of the environmental benefits, is the reduction of nitrogen oxides.

Figure 11. W46 smoke CR versus conventional [17]

6.3.2.5.1 Single-Needle Common-Rail Water Injection System

If the space available in the nozzle holder of the conventional, pressure-controlled HFO injection system does not allow integration of common-rail water injector technology, an alternative system is available.

The water common-rail injector is designed as a single needle-type injector. The nozzle tip of this water injector can basically be located anywhere in the cylinder head. Specially designed nozzle tips and spray patterns guarantee an optimized combustion process, even if the operating position of the injector is virtually horizontal.

6.3.2.5.2 Double-Needle Common-Rail Water Injection System

The big economic incentives of NOx-dependent harbor taxes in the Baltic States mean that some ferries and RO-RO vessels have already been converted to direct-water injection in the form of a so-called retrofit solution. Retrofit means a modern electronic fuel injection system which involves neither significantly redesigning nor considerably rebuilding the engine.

In two steps, water is compressed up to 400 bar. For safety reasons, a mechanical flow fuse is installed upstream of each injector inlet, which immediately locks the inlet in the event of excess quantities. If the plan is to retrofit this system, it is possible to use existing bores in the cylinder head (for pressure transducers or temperature sensors, for example).[18]
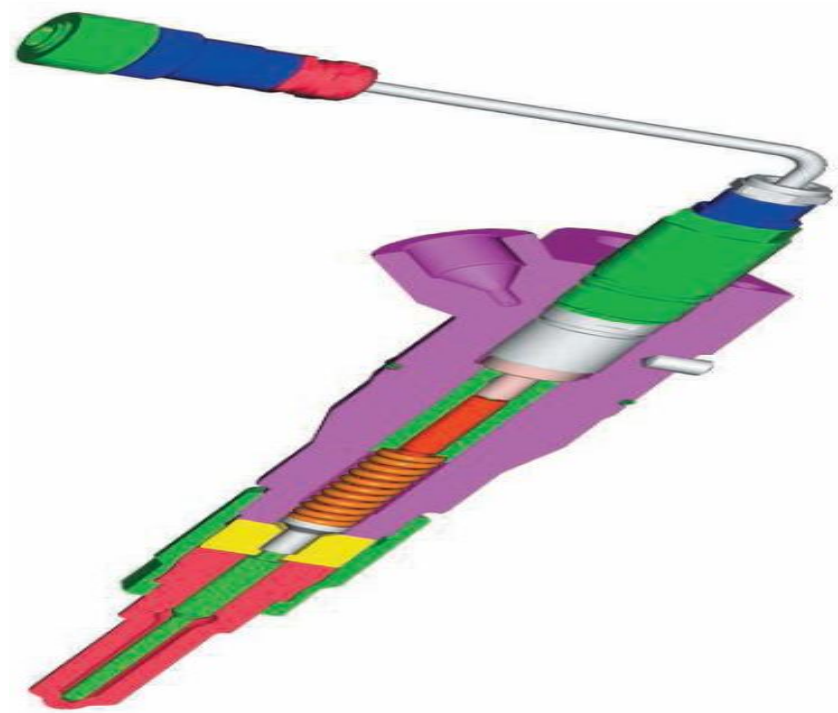
Figure 12. Common-rail fuel injection system [18]

Figure 13. Smoke emissions from common-rail and conventional engine [18]
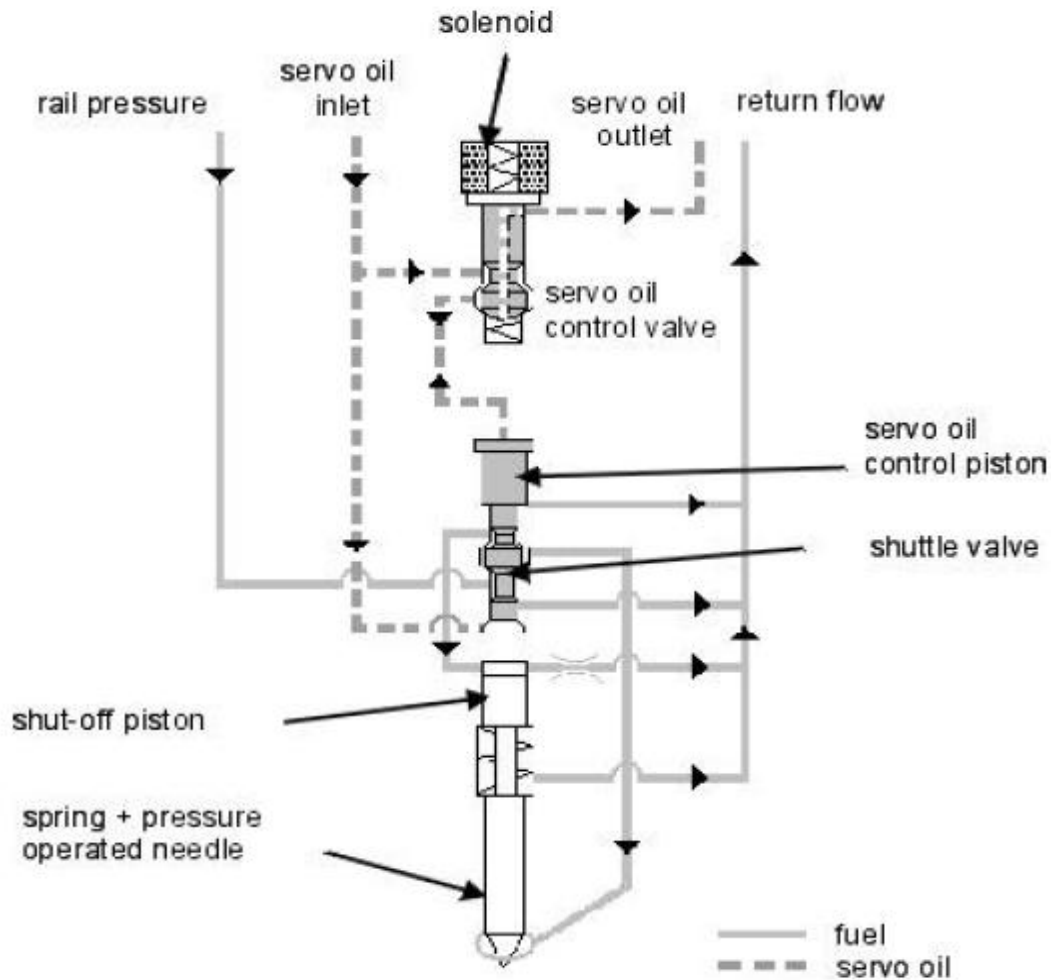
Figure 14. Hydraulic connection scheme of the L'Orange twin-circuit HFO common rail injection system [18]

6.3.3   Exhaust Gas Recirculation (EGR)

Exhaust Gas Recirculation (EGR) lowers the combustion temperature, thus lowering NOx. EGR reduces combustion temperatures by increasing the specific heat capacity of the cylinder gases and by reducing the overall oxygen concentration. EGR tends to increase smoke, by reducing the O_2 concentration, increasing the combustion duration and decreasing the combustion temperature. Because the combustion rate is reduced, the exhaust temperature and thermal load on engine components is increased.

In engines operating on poor quality fuel, external EGR can lead to fouling and corrosion problems. The residue from cooling and cleaning the exhaust gas on ships using heavy fuel oil contains sulphur in a form which is difficult to dispose of.

Kawasaki found that 28% EGR yield a 69% reduction in NOx on a MAN B&W 5S70MC engine, with a small rise in smoke and fuel consumption[21]. Wartsila NSD found 6% EGR yield a 22% NOx reduction on the 4RTX54 research slow speed engine, with a rise in thermal load on engine components and a rise in exhaust temperature.[14]

Wartsila NSD has developed internal EGR in two-stroke engines as an extended measure beyond engine tuning techniques. By reducing the height of the scavenge ports the scavenge air flow into the cylinder is reduced, so more of the burnt gases remain in the cylinder for the next cycle. Lowering the scavenge ports also increases the effective expansion stroke length, resulting in reduced fuel consumption[14]. To overcome the increased thermal load on the engine with internal EGR, Wartsila NSD has developed the "Water Cooled Residual Gas" method which involves injection of water during the compression stroke to bring the temperature in the combustion chamber back to that without internal EGR. The temperature of the combustion chamber is high enough to avoid acid deposits. The injected water also reduces NOx[14].
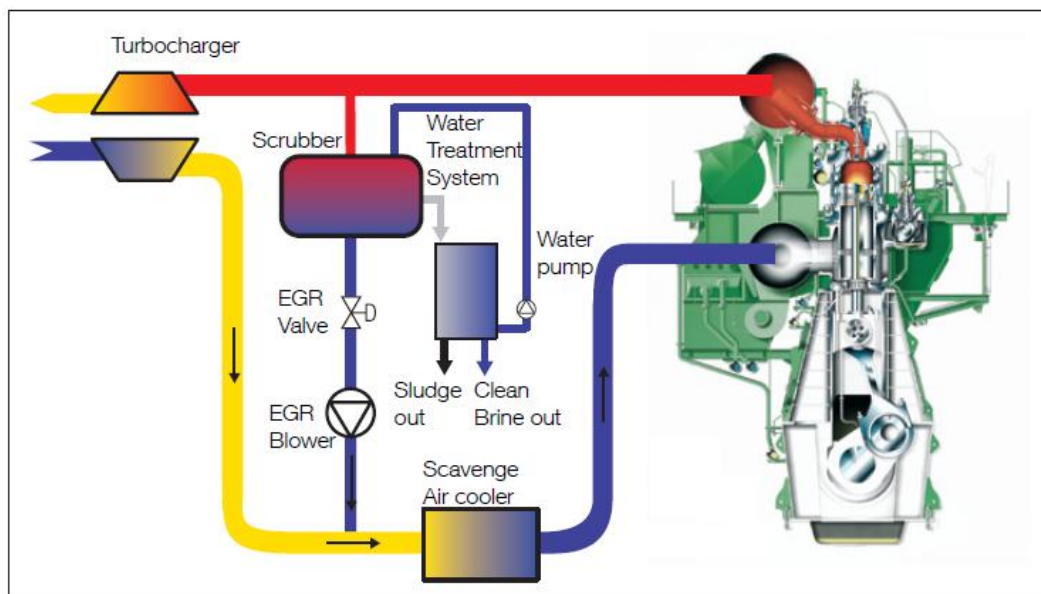
Figure 15. EGR principal layout of 4T50ME-X [19]

Figure 16. EGR system on 4T50ME-X [19]

6.3.3.1 Design of a Retrofit EGR System

The first retrofit EGR system is specifically designed for installation on Alexander Maersk, using know-how obtained during years of testing on the 4T50ME-X test engine in Copenhagen[19].

The first stage was to establish the engine performance on Alexander Maersk, followed by a simulation of the EGR process. The next stage was to specify the EGR components.

The main EGR components are: scrubber, cooler, water mist catcher, blower, shut-down valve, change-over valve, water treatment plant, NaOH dosing system and water cleaning unit. Besides, there is a controlling system for controlling the amount of recirculated exhaust gas, the scavenge air pressure, the dosing amount of NaOH, the circulated scrubber water amount and the scrubber water discharge amount.

As the water flows through the scrubber it will become acidic due to the sulphur content in the exhaust gas which dissolves in the water. A NaOH dosing system is therefore a part of the EGR system.

A significant amount of Particulate Matter (PM) will become suspended in the scrubber water, which will eventually cause failure in the components in the WTP. It is therefore necessary to have a Water Cleaning Unit (WCU) which can remove PM from the scrubber water, and discharge the PM as concentrated sludge into the sludge tank on the vessel. The WCU is designed for cleaning the scrubber water to such an extent that it can be discharged into open sea in compliance with IMO scrubber water discharge criteria when excess of water gain from the combustion process is present.[19]
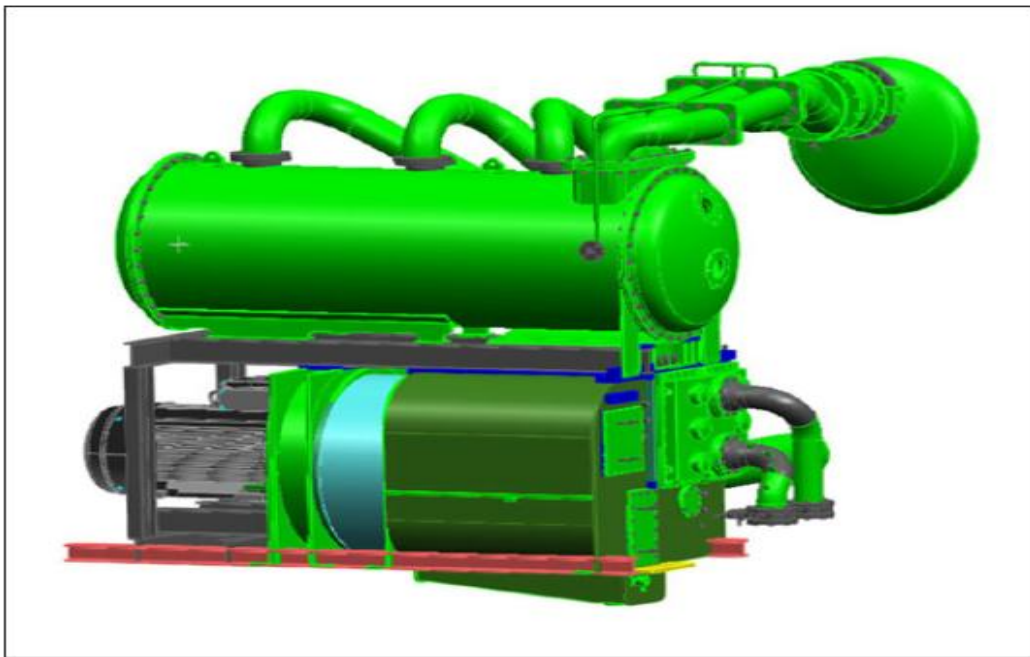
Figure 17. Design of EGR unit [19]
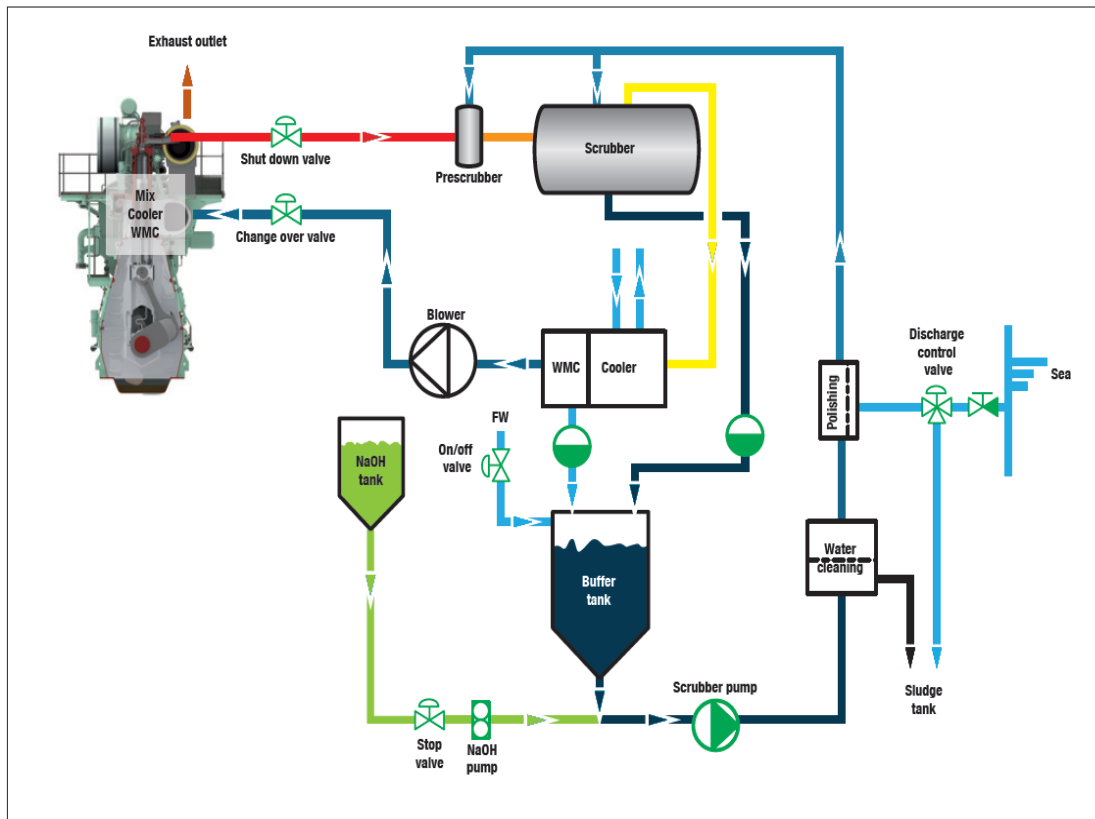
Figure 18. EGR system layout on Alexander Maersk [19]

6.3.4 Direct water injection (DWI)

Another technique for introducing water into the combustion process for lowering NO_X emissions is to inject the water directly into the combustion chamber separately from the fuel (Fig. 19). Under development for Sulzer low-speed engines at Wärtsilä since 1993, this direct water injection (DWI) technique directly reduces cycle temperatures and thus NOX formation. Unlike other techniques for introducing water into the combustion process, direct injection enables the water to be injected at the right time and place to obtain the greatest reduction in to 50 per cent water addition is anticipated, the quantities of water will be substantial. Fresh water generators can be heated using the engine cooling water, or using steam from an exhaust gas economiser. In addition there must be sufficient tank capacity for the water, with the necessary handling system.[20]
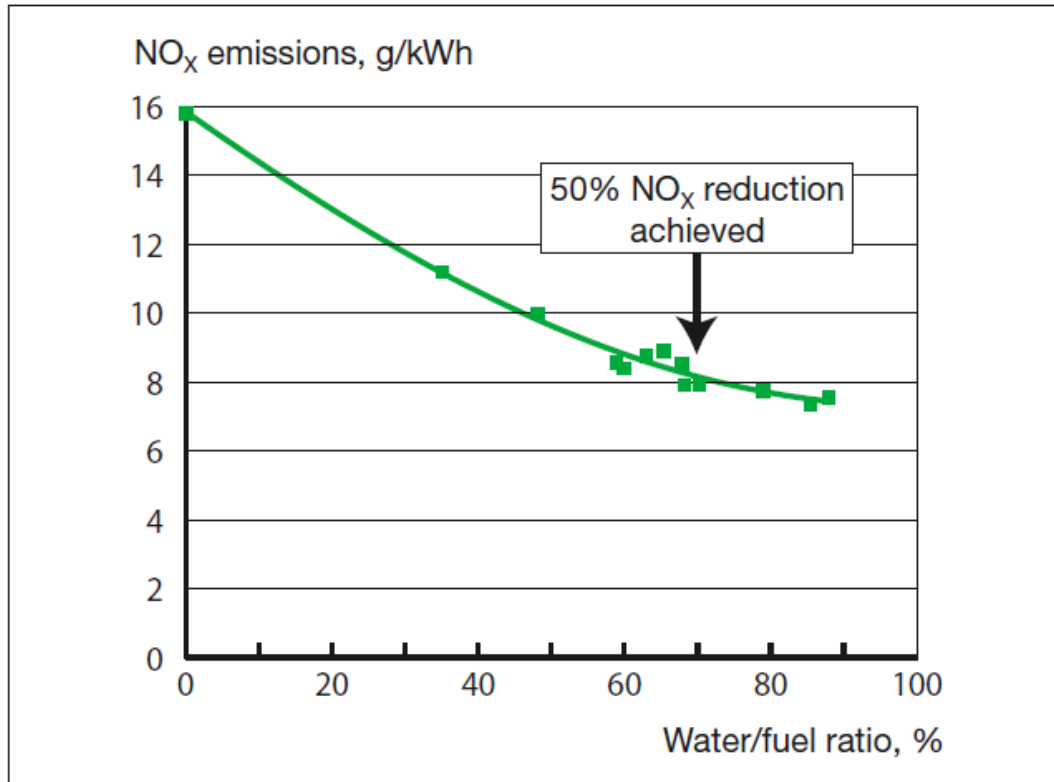
Figure 19. The NOX emissions measured in the Sulzer RT-flex research engine when using Direct Water Injection for different water-fuel ratios in a common-rail system. The testbed results show that 50% reduction in NOX is possible with 70% water.[20]
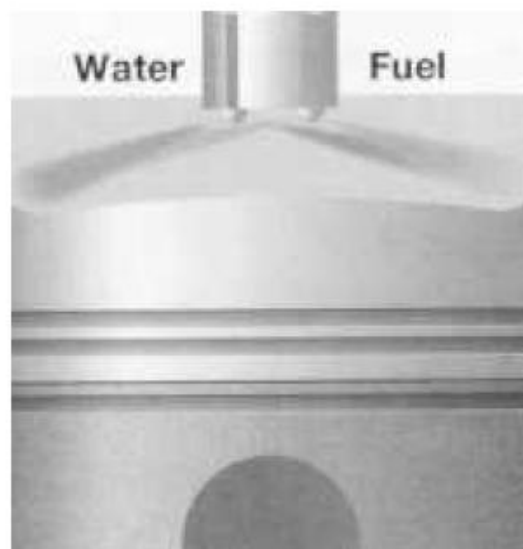
- Water needle and fuel needle in the same injector
- Water pressure 200 - 400 bar
- Fuel pressure 1200 - 2000 bar

Figure 20. The principle of direct water injection [21]

Figure 21. The combined nozzle for DWI [21]

The key element in the design concept is the combined injection valve through which both fuel and water are injected.

The same valve is used for operation on water injection and fuel injection alone. One needle in the combined nozzle is used for water injection and the other for fuel injection. Water injection starts before fuel injection, in order to cool down the combustion space to ensure low NO_x formation (figures 19,20,21)

A high pressure water pump is used to generate water pressure of 200-400 bar. After filtration and dampening of pressure pulses, the water if fed to the injectors via a pressure regulating valve to give the correct injection pressure. For safety reasons the water line to each cylinder is equipped with a sensitive mechanical flow fuse for quick water shut off in case of excessive water flow.

Water injection timing and duration is electronically controlled and can easily be adjusted by programming the control unit which allows selection of the optimum settings for each application. The amount of water injected , i.e the water/fuel ratio is controlled by the duration of injection. [21]
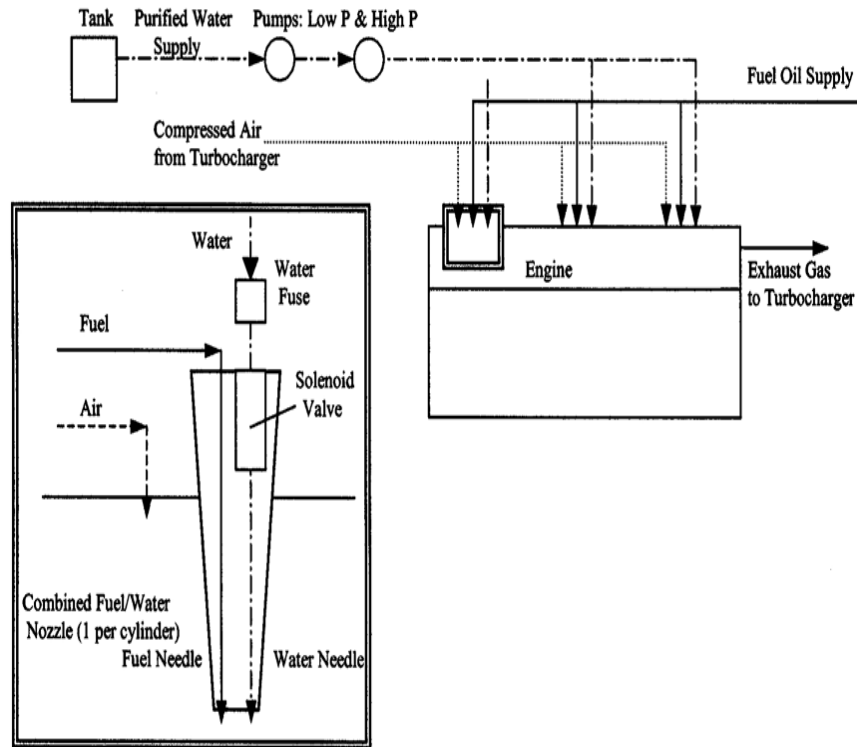
Figure 22. DWI schematic diagram [21]

6.3.5 Inlet Air Humidification

A second, widely acclaimed technology for reducing NOx pollution from diesel engines is the humidification of inlet air. This technology is able to reduce NOx formation by up to 65%. In the air humidification system the turbocharged combustion air is saturated with water vapour produced aboard the ship using sea water and engine heat. This lowers the temperature peaks in the combustion chamber, which are normally the main reason for NOx formation. Inlet air humidification is characterized by extremely low operating costs due to sea water usage, decreased lube oil consumption, very low maintenance costs and a very high availability factor[22].
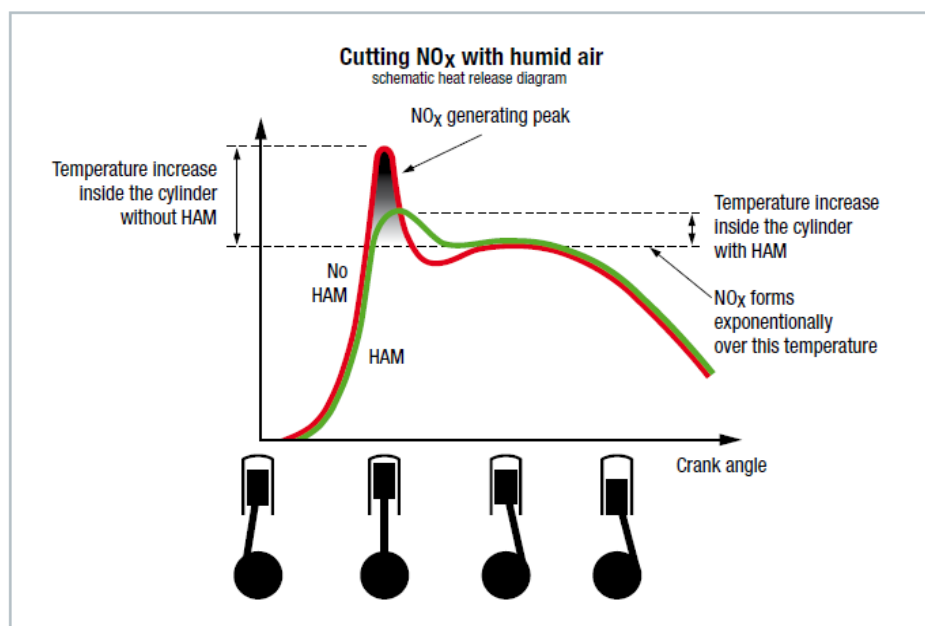
Figure 23. Cutting NOx with humid air-schematic heat release diagram [22]

6.3.5.1   *Inlet Air Humidification Principle*

Over 90% of NOx formation results from combustion temperature peaks. The principle of humidifying system ("Humid Air Motors – HAM") is to humidify the inlet air in order to lower these temperature peaks. The HAM system humidifier produces saturated air.

The ability of water to decrease the formation of NOx is exploited in the same way as with fuel water emulsification, but the quantity of water added is much higher and the heat for water vaporization is taken from the compressed air after the turbocharger or other engine-related heat sources.

When the water vapor is mixed with the compressed charge air, two mechanisms can be identified:

- Increase of the specific heat capacity of the mixture,

- Dilution of the charge air: water vapour replaces air.

The quantity of water (in g/kg dry air) which can be injected into the inlet air depends on the temperature and the pressure of the mixture.

As shown in the diagram in *figure 24*, when the air temperature rises so does the quantity of water it is possible to vaporize.

In this area inlet air humidification has an outstanding advantage, since it uses the heat of the engine to bring the saltwater up to temperature. No external energy source is needed. In addition to the heat of the charge air after the turbocharger, in many applications heat from the engine coolant and exhaust gases can be introduced into the charge-air to increase its capacity to absorb moisture.

With inlet air humidification, a NOx reduction level of 40% is achieveable without using additional heating of the intake air and a level of 65% when additional heat is introduced from the engine coolant or exhaust gases.
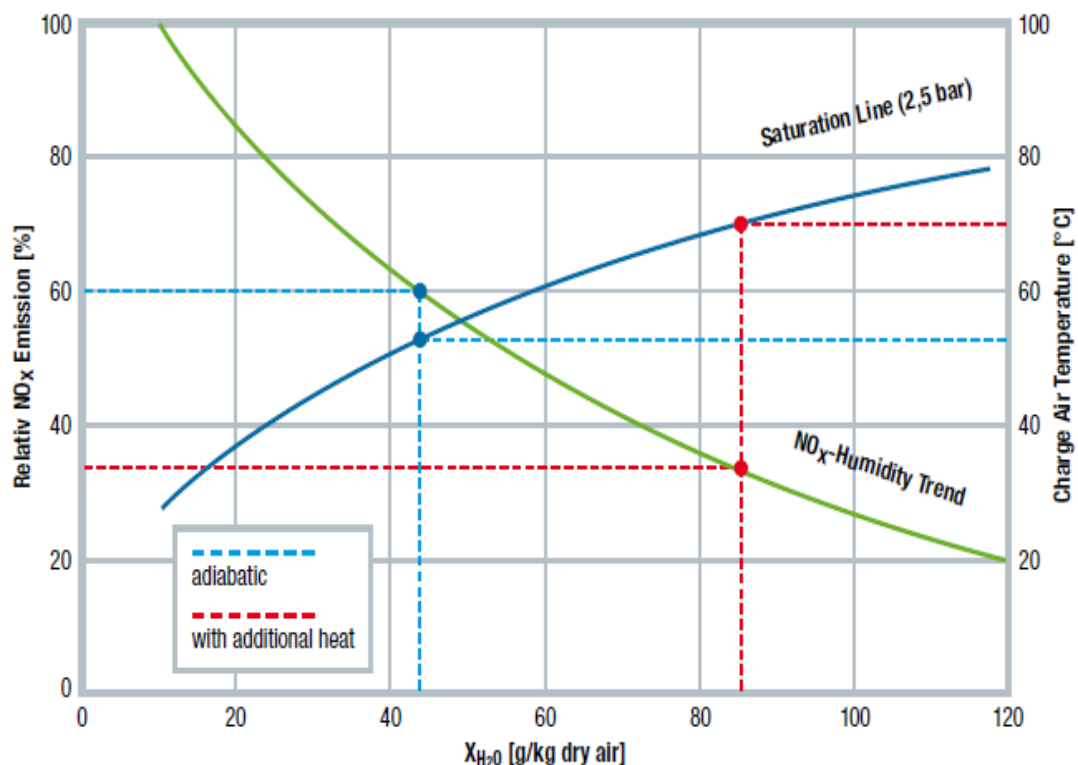
Figure 24. NOx -humidity trend [22]

6.3.5.2 *Description of Inlet Air Humidification Process*

Figure 25 illustrates the process of inlet air humidification [22]:

1) Filtered saltwater is pumped to the catch tank to replace evaporated and purged loop water.

2) The air humidification system itself cycles water in a loop between the catch tank and the Humidification tower ("HAM vessel")

3) A heat exchanger between the catch tank and the HAM vessel heats the saltwater using an on-engine heat source.

4) Three injection stages spray the heated saltwater into the charge air.

5) At the same time the compressed charge air from the exhaust turbocharger bypasses the charge air cooler and is piped into the HAM vessel air inlet. Flowing through the HAM vessel, the charge air absorbs the water. Due to the high loop capacity of the water all particles (incl. salt) fall back into the catch tank and, over a certain salinity level, are purged. Thus no salt from the saltwater can enter the engine.

6) To avoid tiny droplets reaching the combustion chamber, the humidified charge air passes through a high-performance mist catcher at the end of the humidification tower.

7) This humidification leads to saturated charge air which is fed into the engine.
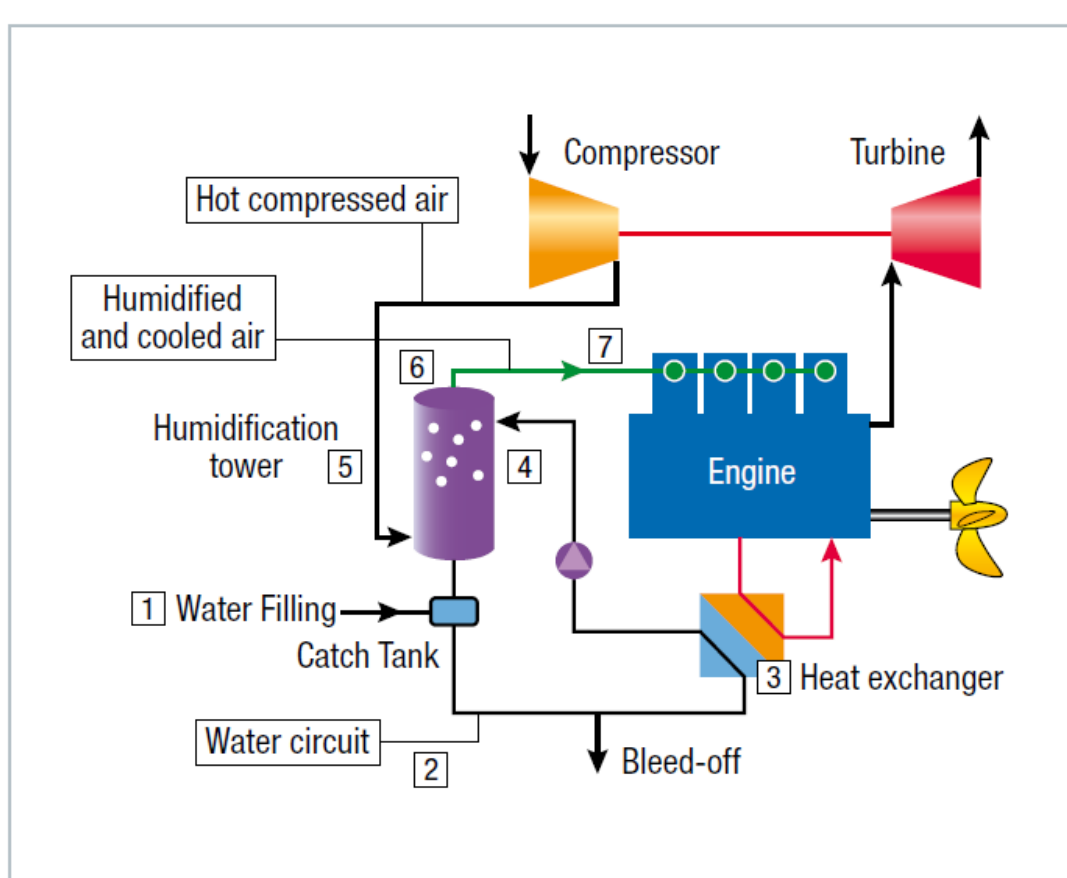
Figure 25. Schematic view of inlet air humidification process [22]

6.3.6 Water fuel emulsion

With regard to NOx emissions, water emulsions showed a significant reduction in NOx emission with a relatively limited penalty in terms of fuel oil consumption. For the two-stroke engine, we have seen a 10% NOx reduction for each 10% water added.

6.3.6.1 *Homogenisers for water emulsion*

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

However, if the engine is to be operated on diesel oil, it may be necessary to add additives to stabilise the emulsion. The location of the homogeniser in the fuel oil system is shown in Fig.26. The same position is used irrespective of whether the homogeniser type is mechanical, ultrasonic or high-pressure injection[23].
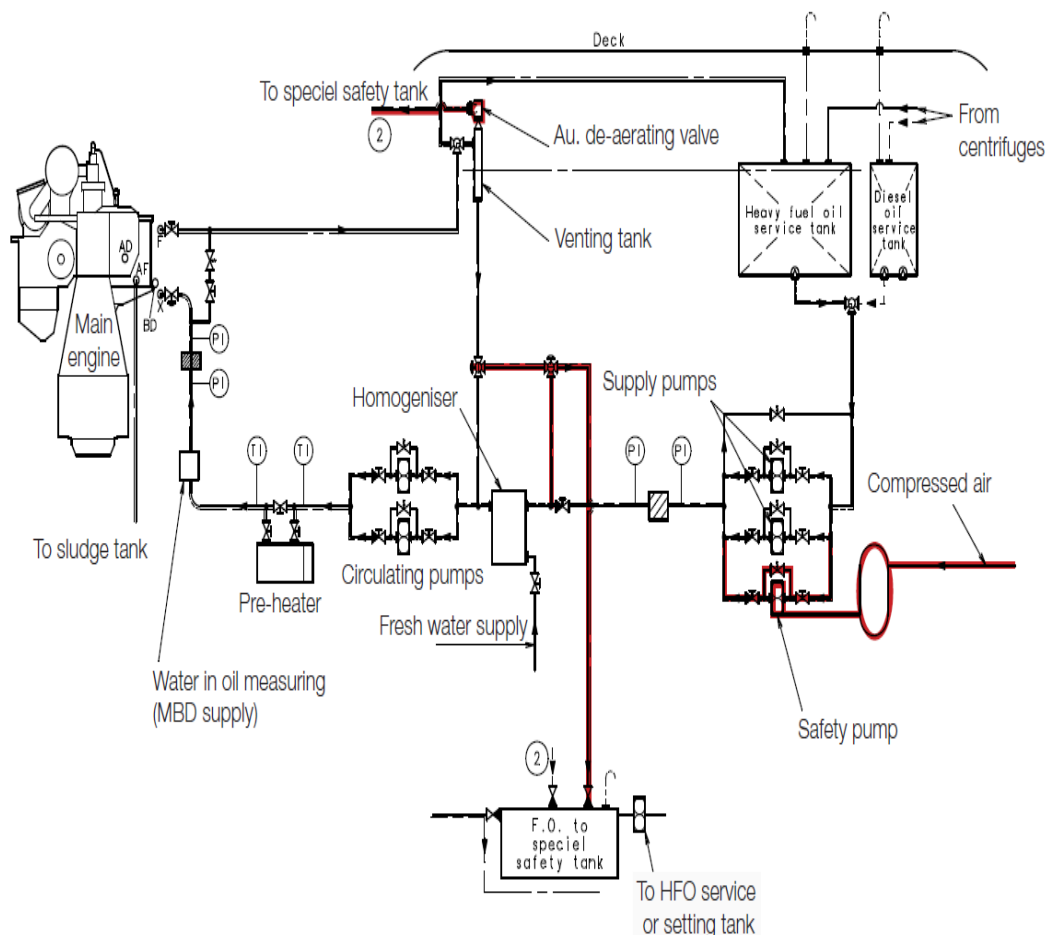
Figure 26. Pressurised fuel oil system with homogeniser, incl safety pump and drain tank[23]

The addition of water to the HFO by homogenisation increases viscosity. To keep the viscosity at the engine inlet at 10-15 cSt, max. 20 cSt, it may become necessary to raise the temperature to more than the $150^{o}C$, which is standard today (max. $170^{o}C$ at 50% water) and, accordingly, to raise the fuel oil loop pressure in order to avoid boiling of water.

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

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

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

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

- Optimal injection rate shaping can be achieved both without and with any water content.

- ''Free rate shaping'' allows the use of large water amounts even at low engine load as pre-injection can be used to compensate for ignition delay.

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

The working principle of the high-pressure injection system is water sprayed into the fuel by a special nozzle at 100 bar pressure at the nozzle tip (see Fig.27). The high-pressure pump is "frequency controlled", and can deliver the needed water amount at constant pressure at all times.[23]

Summarizing [15]:

- NOx reduction potential typically: up to 20%

- Water-to-Fuel ratio typically: 0.3

- Reduced smoke formation especially at low load

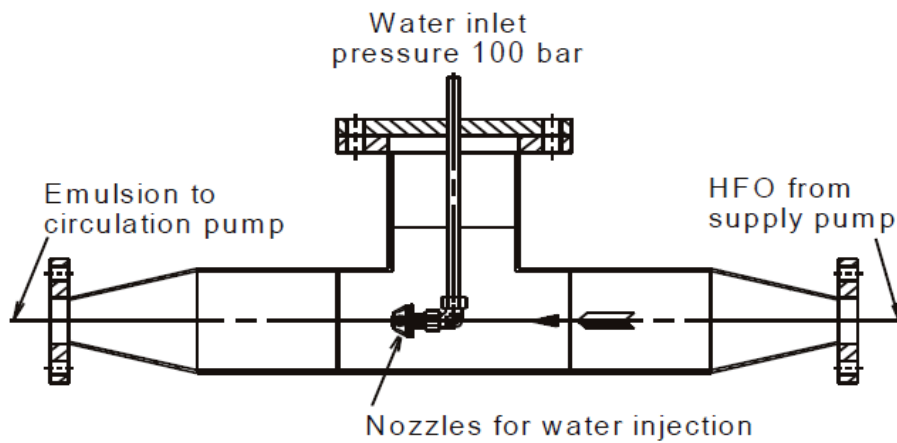- Laboratory tested technology but no field installation (=> no long term experience)

Figure 27. High-pressure (100bar) injection of water in the fuel line [23]

Figure 28. Pump unit [23]

6.3.7 Selective Catalytic Reduction (SCR)

An alternative way of meeting the IMO Tier III NOx limits is to install a SCR reactor. In the reactor, NOx is reduced catalytically by a suitable reducing agent to nitrogen and water, see Fig. 29.
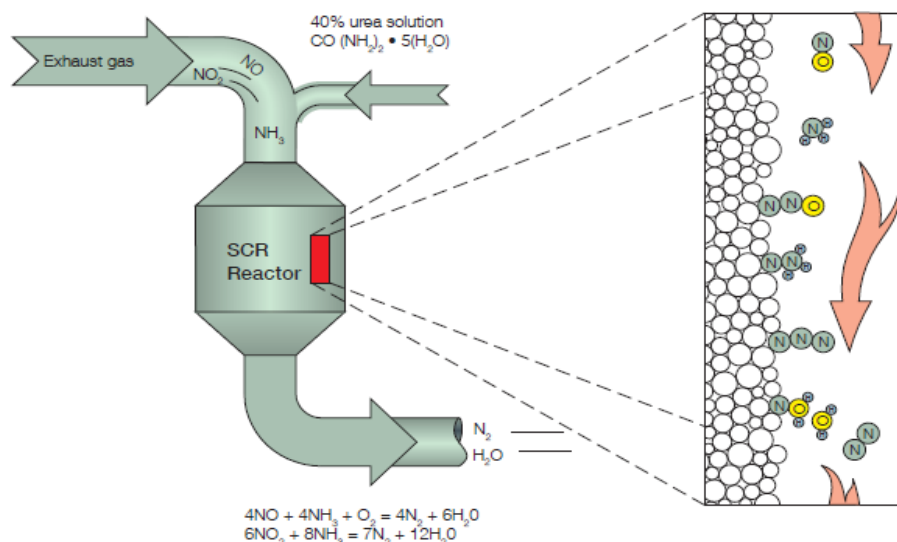
Figure 29. Principles of the SCR system [19]

Compared to other NOx reducing technologies, the SCR technology has the advantage that it is a proven technology. SCR reactors have been used in power plant applications since the late seventies, and MAN Diesel & Turbo was involved in one of the first marine applications in 1989 [19]. However, whereas the technology involves mature and robust power plant applications, the technology still needs to be matured for daily and continuous marine operation on HFO. Therefore, MAN Diesel & Turbo is involved in a targeted development of this technology together with a catalyst manufacturer and engine builder.

The application of high pressure SCR (normally used on two-stroke engines) is more tedious than similar installations of low pressure SCR after the turbochargers (normally used on four-stroke engines). Due to the high turbocharger efficiency application and the high energy efficiency of two-stroke diesel engines, the exhaust gas temperatures after the turbocharger are lower compared to the temperatures obtained on four-stroke diesel engines. For two-stroke diesel engines, temperatures are typically in the range from 230 to 260°C after the turbocharger. Normally, the SCR inlet gas temperature should ideally be around 350°C when the engine is operated on HFO. Currently, this temperature condition has called for a solution

where the SCR is situated on the high pressure side of the turbine. Dependent on the engine load, this makes it possible to obtain SCR inlet temperatures, which are between 50 and 200°C higher than the temperatures which can be obtained as SCR inlet temperatures with SCR placed after the turbocharger, see Fig. 30 [19].
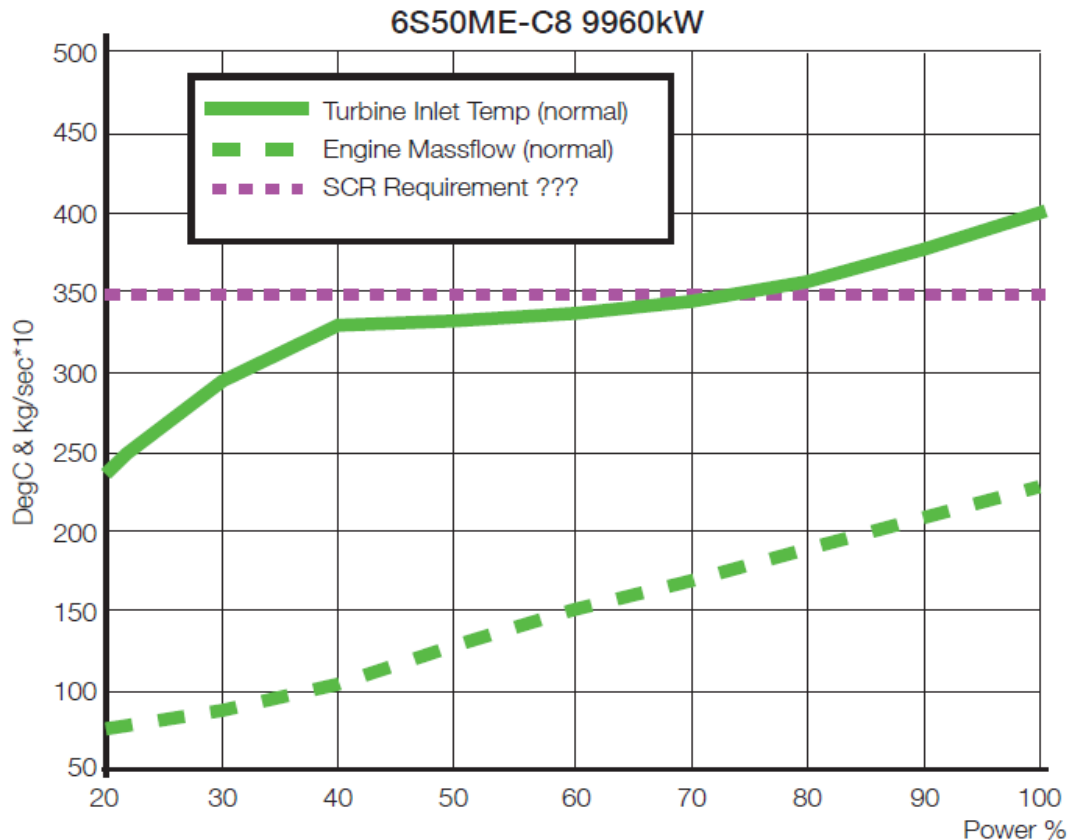

Figure 30. Measured turbine inlet temperatures[19]

The SCR has a significant heat capacity and because the SCR is fitted before the turbocharger this constitutes a challenge in terms of control and regulation. Due to the heat capacity, it is necessary to bypass some of the exhaust gas directly to the turbocharger during engine start-up and possibly also under extreme acceleration in order to ensure sufficient energy input 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.

Despite this arrangement, the required exhaust gas temperature for trouble-free SCR operation may not be obtained. This is especially a problem at lower loads where the temperature is well below 300°C, see Fig. 31. As a countermeasure for the too low exhaust gas temperature, it will be possible to increase the exhaust gas temperature by

utilizing a turbine bypass possible in combination with variable turbochargers. This measure decreases the air flow through the engine and thus increases the exhaust gas temperature. The preliminary calculations shown in Fig. 31 reveal that it is possible to tailor the desired exhaust gas temperature for a broad range of load points. However, the figure also clearly shows that the exhaust gas temperature in the lowest IMO load point remains a challenge [19].
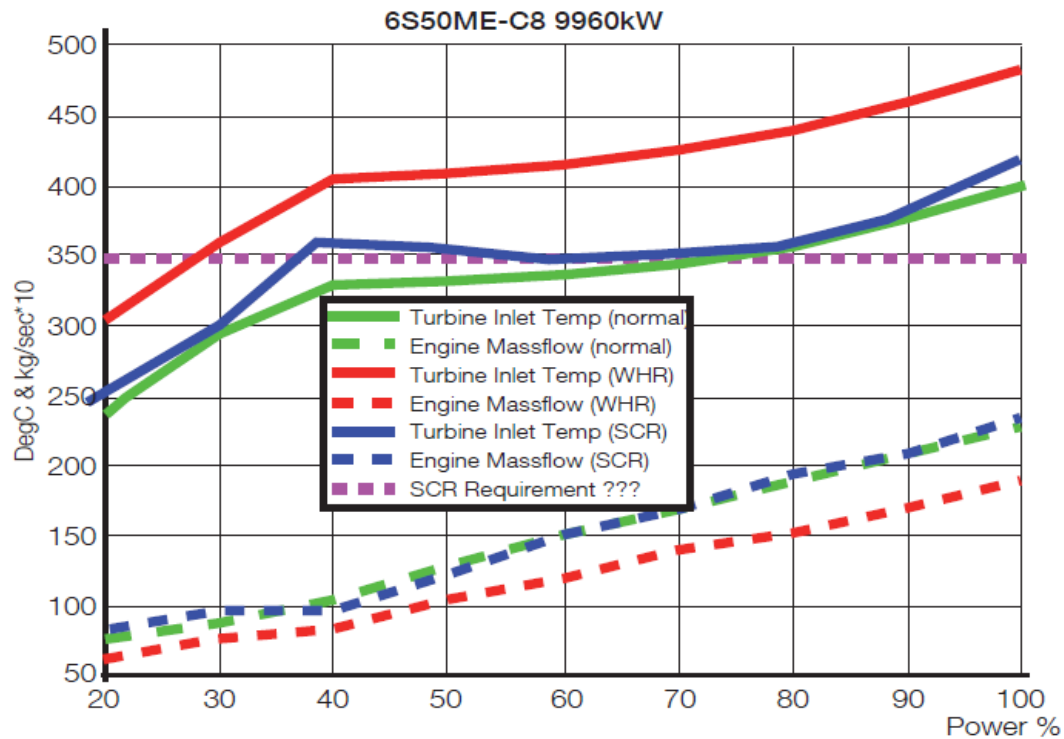

Figure 31. Manipulation of exhaust gas temperature by turbine bypass[19]

Reduction of NOx emissions can also be accomplished with a SCR system with hydrocarbons as the reducing agent. The system can use the on-board fuel tank as its reservoir and a control system to time the injection process to the engine timing to optimize the NOx reduction process. Sumiya [19] have shown 30 percent NOx reduction at a 450 ºC exhaust temperature with diesel fuel sprayed ahead of the catalyst bed. This approach has not been tested on any marine engine. As it can be summarized, SCR systems are also well established technologies and are widely adapted in new marine vessels. [19]

6.3.8 NOx Abatements technologies

Table 22 show the effectiveness of some of these technologies in reducing NOx emissions, based on known shipboard installation and field testing.[24]

Table 22. Combinations of advanced internal engine modifications, NOX reduction efficiency[24]

	NOx
Basic IEM (Slide Valves)	-20%
Advanced IEM	-30%
Direct Water Injection	-50%
Humid Air Motor	-70%
Exhaust Gas Recirculation (ships using RO but Switching to MD (accounting for SO2 & PM reductions)	-35%
Exhaust Gas Recirculation (ships originally using MD)	-35%
Selective Catalytic Reduction	-90%

6.4 SOx Abatement techniques

6.4.1 Scrubbers

Exhaust gas scrubbers can remove the majority of SOx emissions from the exhaust stream, as well as a significant proportion of the particulate matter. Various systems developed for marine use, use sea water, fresh water or chemicals to wash out or neutralise the SOx.

Typical absorbents for wet sulphur removal process [9]:

- Lime(stone)

- Caustic soda

- Seawater and fresh water

- Ammonium Hydroxide

- Magnesium Hydroxide

Caustic soda and seawater scrubbers are the feasible choices for installation on board.

6.4.1.1 *Seawater and fresh water Scrubbers*

Sea water scrubber exploits the natural alkalinity of water to neutralize the dissolved sulphur dioxide from the exhaust gas. Alkalinity reflects the ability to react with acids and neutralize them. When acid is added to high alkalinity water, the pH of water decreases and the buffering capacity is used [25]:

- slow pH decrease to 6

- rapid drop from pH 6 to 5.5

- weak buffering capacity from pH 5.5 to 4.5

- buffering capacity used at pH 4.5, no alkalinity left

High alkalinity improves the neutralization and simultaneously the water can stand the process better, without collapse in pH. Areas with high alkalinity are beneficial for sea water scrubber. Cleaning efficiency is slightly higher. Receiving waters can tolerate better the wash water from the scrubber.

An example of seawater and freshwater scrubbers installed on a ship, is the vessel 32,389 GT Ro-Ro built in 2006 by Flensburger Schiffbau Gesellschaft in Germany.

The vessel is equipped with a 20 MW MAN B&W 9L60MC-C main engine, giving her a service speed of 22.5 knots and the vessel is trading a fixed North Sea route between Gothenburg in Sweden and Immingham, the UK [25].

The 20 MW installation will be the biggest scrubber in the world on a seagoing vessel. The installation of the main scrubber components was carried out during a docking in June/July of 2009. The final installation work of pumps, coolers, piping systems and electrical systems has been carried out in service during the fall/winter of 2009 and was finished by the end of February 2010. Commissioning and initial testing of the system will follow immediately after finishing the installation.

The system chosen for DFDS is capable of running as an open loop pure Sea Water (SW) scrubber as well as a closed loop Fresh Water (FW) scrubber. The system will run as a pure SW scrubber during normal sea passage. When entering coastal areas, ports or an estuary, the system will automatically be switched over to a closed loop FW scrubbing [25].
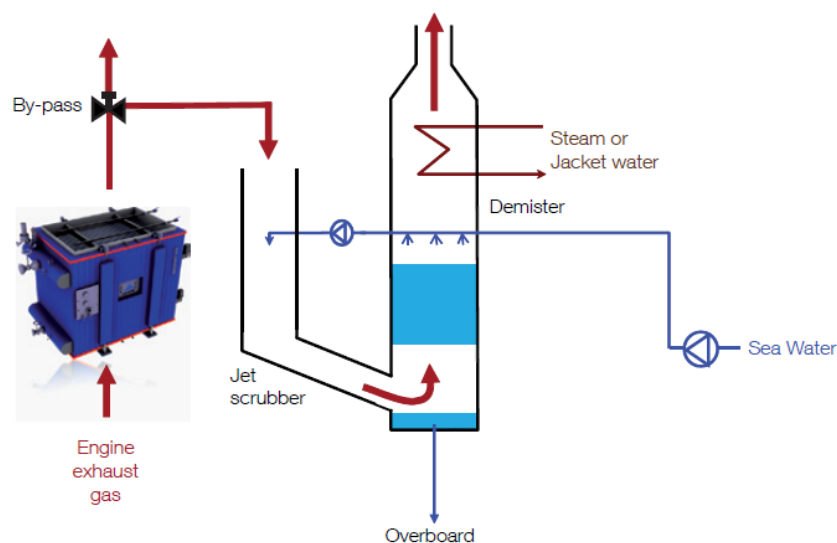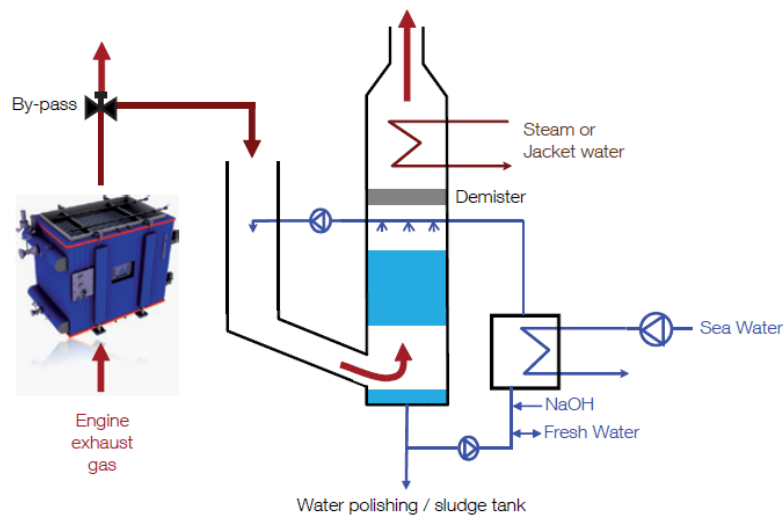

Figure32 Running in sea water mode [25]

Figure 33. Running in fresh water mode [25]

6.4.1.1.1 Sea Water Scrubbing

Sea water scrubbing is intended as the main running mode. Sea water is supplied via the vessel's normal cooling water pumps, through a booster pump for a one time passage through the scrubber. The amount of sea water through the scrubber ensures sufficient reaction to the sea salts and sufficient dilution to allow the scrubber water to be discharged directly into the sea without further cleaning. All values and criteria for wash water discharge with regard to PH values and PAH are fulfilled.

To ensure sufficient Sea Water, as much as 900 m^3/hr has to be pumped (at 20 MW engine power). However, as the engine is normally running only around 80% MCR, the sea water pump is controlled through a frequency converter, adapting the pump power to the engine power and thus saving KW power. The maximum fuel penalty for running the scrubber system in sea water mode is expected to be around 1% main engine power.

6.4.1.1.2 Fresh Water Scrubbing

When entering coastal areas or ports where no discharge is allowed, the system will be switched over to fresh water scrubbing. The switch will be carried out automatically by a push button request from ECR or BC.

When running in fresh water mode, 99% of the fresh water is recirculated in a closed loop from a special fresh water/dosage tank through the scrubber, using the same

booster pump as used by the SW mode. Thus, only a fraction of the water will have to be cleaned and discharged.

Due to the addition of NaOH as a SO2 neutralising agent to the scrubber fresh water, a significantly lower amount of water is needed. It is expected that a fresh water maximum of 200 m^3/hr (at MCR) is sufficient. As this is only around one fifth of the needed sea water power, this will of course significantly reduce the necessary power costs to run the system [19].

To be able to neutralise the SO_2, NaOH is added via a small dosage pump into the dosage tank. If running on HFO, fuel with a 3% SO_2 content, calculations confirmed by the prototype tests, will show a needed NaOH consumption of approximately 10-12 kg/MWh.

Since the FW mode is used only during harbour or coastal sailing, the main engine power will be low and the sailing time will be short, further reducing the NaOH consumption. A typical arrival to port will be maximum two hours and maximum 2-3 MW engine power, giving a total consumption of around 50 kg NaOH.

During FW running, no water is discharged from the vessel. As the running time is short the circulated amount of fresh water is fully capable of consuming the PAH and SO2 extracted from the exhaust gas. When leaving port and switching back to SW mode, the now polluted fresh water in the fresh water system tank will be cleaned through a filtration unit working independently of the scrubber system.[19]

Table 23. Assumed reduction efficiencies of the sea water scrubbing technology (SWS)[19]

	NOx	SO2
Reduction efficiencies SWS	0%	75%

6.4.1.2 *Caustic soda Onboard*

The typical commercial solution is a liquid with a concentration of 50%. It has a density of 1.52 t/m^3 and a pH of 14. It solidifies at 12°C, and is typically transported warm. The caustic soda can be bunkered from trucks via filling connections in the bunker stations. The storage tank can be of normal shipbuilding steel. Based on price fluctuations of caustic soda during the last 20 years, the cost is between 0.5 and 4% of the fuel costs.[26]
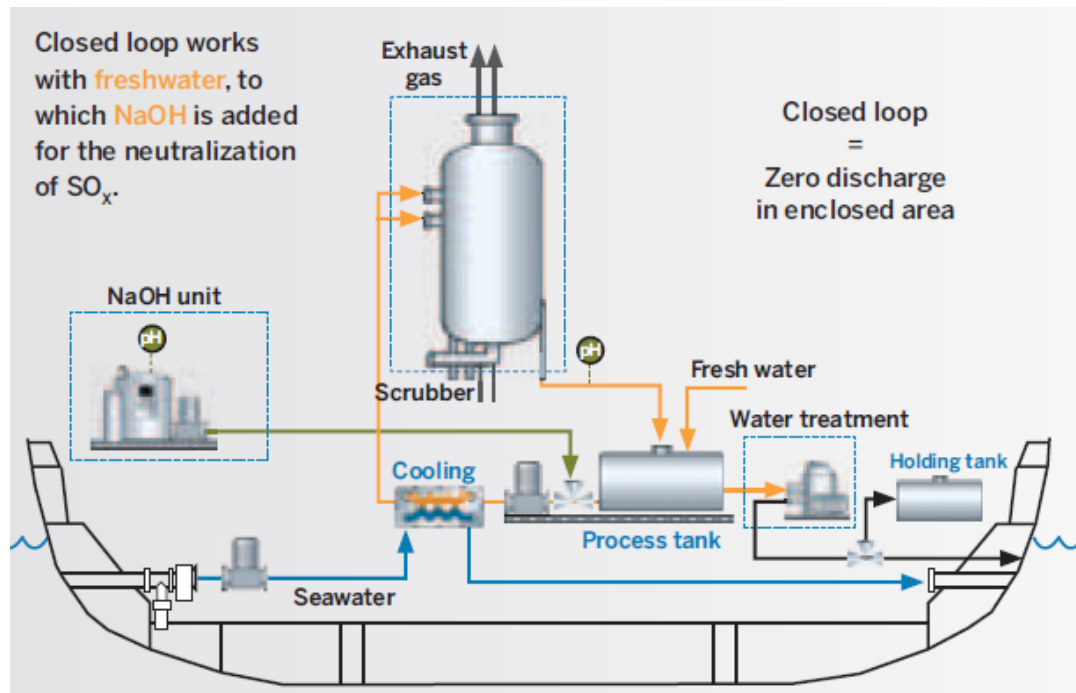
Figure 34. Sulphur removal from exhaust gas[26]

6.4.2 Low Sulphur fuels

The most straightforward method of reducing SOx emissions is to reduce fuel sulphur content. There is a limit to how low the sulphur content of heavy fuel oil can be reduced. Heavy fuel oil is largely composed of the thick residue from the crude oil refining process, to which lighter components have been added to bring it to a useable consistency. It is black in colour. The majority of shipping runs on heavy fuel oil. IMO Marpol Annex VI will allow global fuel sulphur content of 3.5% until 2020, a further decade from now. By comparison, the diesel fuel used for road transport (ULSD) contains only 0.0010% sulphur by mass. States requiring lower fuel sulphur can make their own rules or declare Emission Control Areas (ECAs) under IMO MARPOL Annex VI. Higher quality marine diesel fuels are available, but at a greater cost. These lighter fuels are known as Marine Diesel Oil (MDO) or Marine Gas Oil (MGO). ULSD, MGO and MDO are known generally as distillates. Some ships use MGO or MDO in their auxiliary engines for generating electricity. MDO and MGO are available at low sulphur content, down to around 0.1%. MDO and MGO are not generally available in Australia, and if ships were required to use fuel other than heavy fuel oil in or near port, they would either bring MDO or MGO with them or use Australian made ULSD, which has a very low sulphur content. Natural gas is another alternative fuel, but is not as easy to implement as low sulphur distillate.[9]
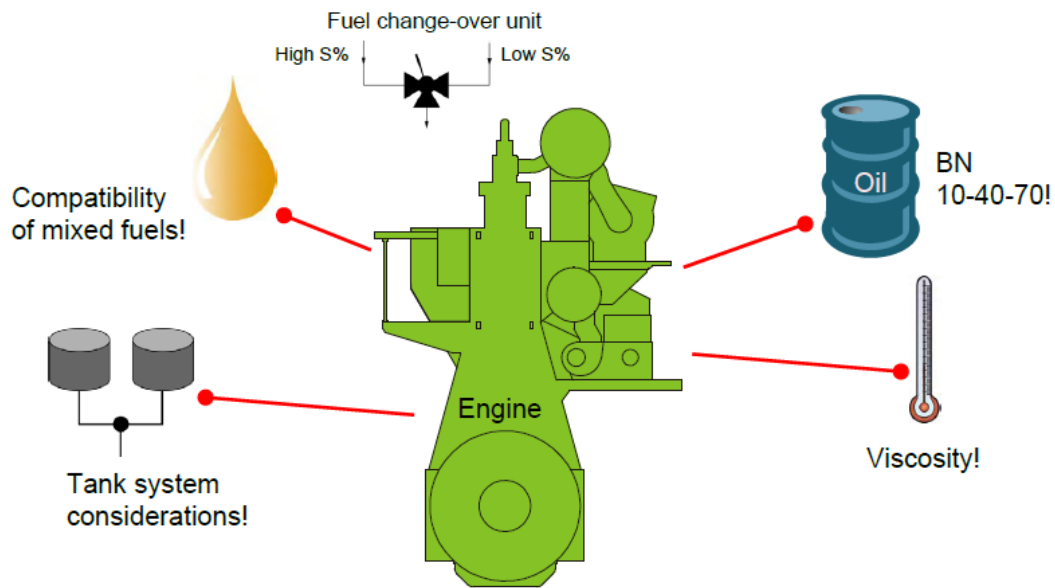
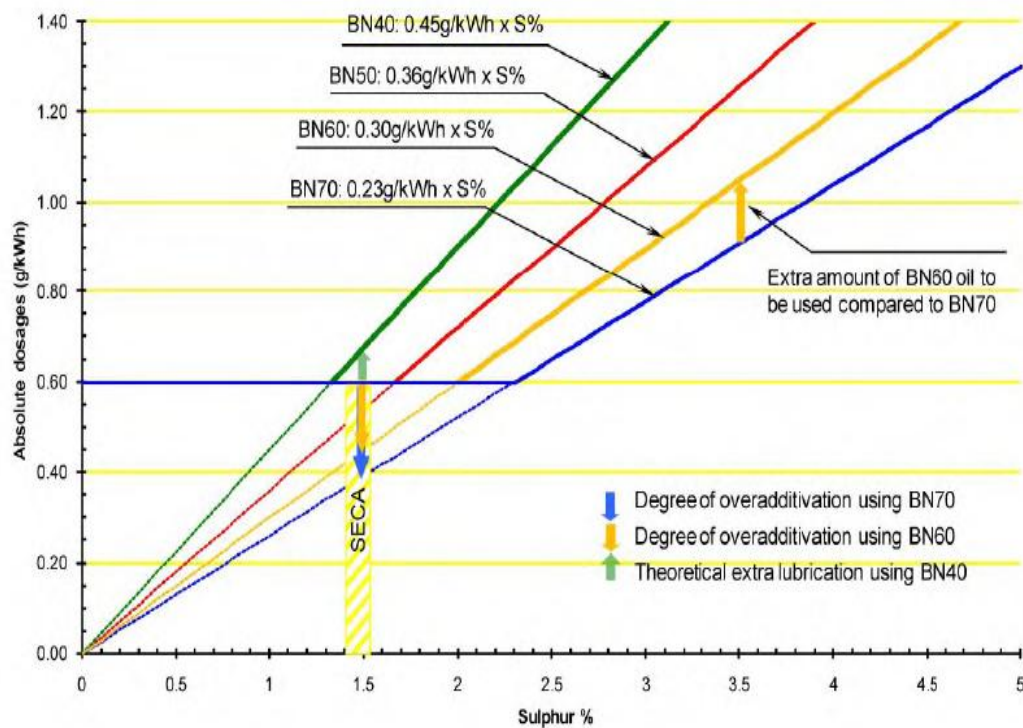*Figure35. Low-Sulphur Fuel Operation[9]*

Figure 36. Low-Sulphur Fuel Operation[9]

6.4.2.1 *Fuel switching*

Creation of SO2 emissions from fuel combustion is directly related to the sulphur content of fuels. Therefore the reduction efficiency of fuel switching is related to the reduction in sulphur content of the fuels. It is likely that fuel switching will be done by using low sulphur residual oil (RO) rather than using marine distillate (MD). This

is because the premium for low sulphur fuel is €200020-89 per tonne for RO (BecipFranlab 2003) and around €110 and €130 per tonne for switching to 0.2% and 0.1% sulphur MD10 respectively. Therefore the following two scenarios were further considered [27]:

1. Switching from 2.7% sulphur to 1.5% sulphur and

2. Sswitching from 2.7% sulphur to 0.5% sulphur.

A reduction in the sulphur content of fuels will reduce PM emissions, however this is difficult to quantify with the extent of currently available data and many emission measurement methodologies do not include PM reductions from a reduction in the sulphur content of fuel [27]. A US EPA study (US EPA 2003 3) estimates PM reductions for dropping from 2.7% to 1.5% sulphur fuel as 18%. PM reductions for dropping from 2.7% to 0.5% sulphur fuel will therefore be most likely greater than 18%, but less than the 63% reduction seen from switching to marine distillate (US EPA 2003 3). As a working assumption, a figure of 20% PM reduction is used in this study. The actual reduction will depend on various factors including the source of crude oil and the nature of the petroleum refining operations used to produce the

RO.[27]

Table 24. Assumed reduction efficiencies of fuel switching [27]

	Fuel S %	NOx	SO2
Fuel Switching 1	2.7 to 1.5	0%	44%
Fuel Switching 2	2.7 to 0.5	0%	81%

6.5

6.6 CO2 Abatement techniques

6.6.1 Turbocharger +VTA control system

The turbochargers operate on a constant pressure system, with scavenge air pressures up to 3.9 bar. There are one to four turbochargers, all located high on the side of the engine, outboard and beneath the exhaust manifold. This allows an efficient arrangement with the scavenge air cooler and its associated water separator unit located immediately below the turbocharger and adjacent to the scavenge air space on the piston underside.

However, in some special cases with smaller engines having a single turbocharger, the turbocharger and air cooler can be arranged at the end of the engine.

Electrically-driven auxiliary blowers are provided to supplement the scavenge air delivery when engines are operating below 30 per cent load. This is necessary because, at such low engine loads and speeds, the turbochargers cannot deliver the necessary air for the gas flow process of the two-stroke cycle.

This paper only refers to marine engines directly driving fixed-pitch propellers. Thus the engines follow a propeller characteristic (power versus shaft speed) fixed by the

ship/propeller relationship. Full load of the engine is the contracted maximum continuous rated (CMCR) power at the CMCR speed.

MAN is testing an exhaust gas recovery system at sea fitted on board a Maersk Line containership, while to reduce CO2 emissions, the company is working on variable turbine area (VTA) applications, auto tuning and engine/propeller and speed optimisations [38].

Optimization of CO_2 emission and fuel efficiency of a 6S50ME-B8 engine with TCA66-21V variable turbine area turbocharger(VTA)

- Turbocharger + VTA control system integrated into ME-B engine control system

Turbocharger cut-out:

- 1 of 1 T/C, 15% power, only emergency (VTA tech)

- 1 of 2 T/C, 35% power, only emergency

- 1 of 3 T/C, 66% power

- 1 of 4 T/C, 68% power

- Change over time 30 min.

- Change over at stopped or dead slow engine condition
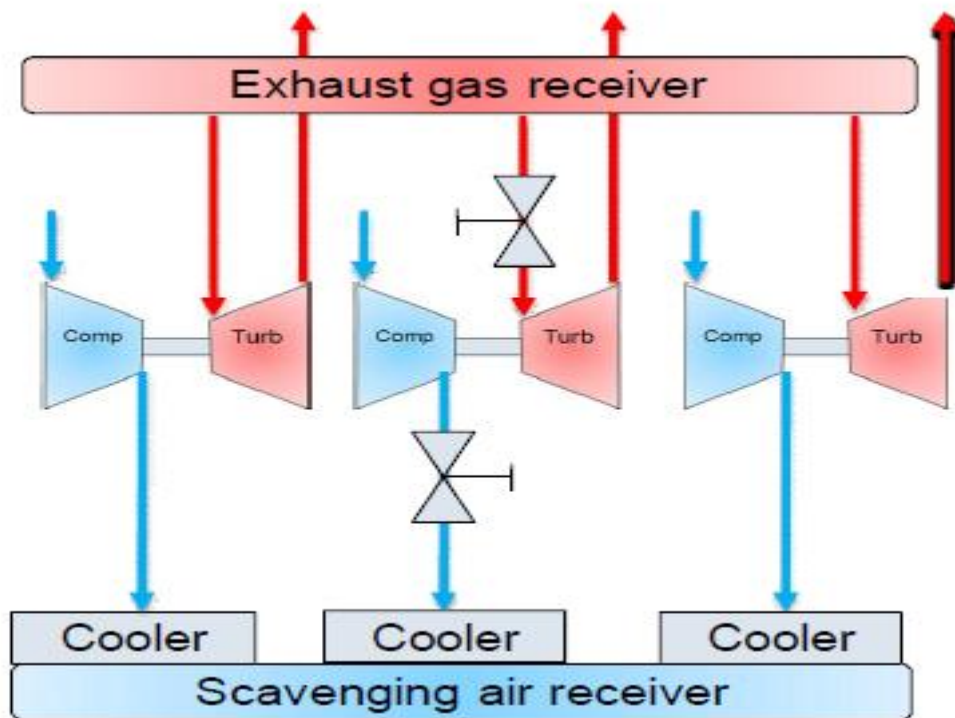
- Fully integrated system with interlock to ME ECS.

Figure 37. Low load Operation T/C cut out: concept [38]

Engine load:

75-100%: TC#L+S

< 75%: TC#L

Effect:

At low load the effective turbine area is smaller and therefore the scavenge air pressure higher.

Engine scope:

A dynamic TC cut-out system for engines with 1-2 turbochargers and a competitive product to VT, EGB and to some extent TC cut-out.
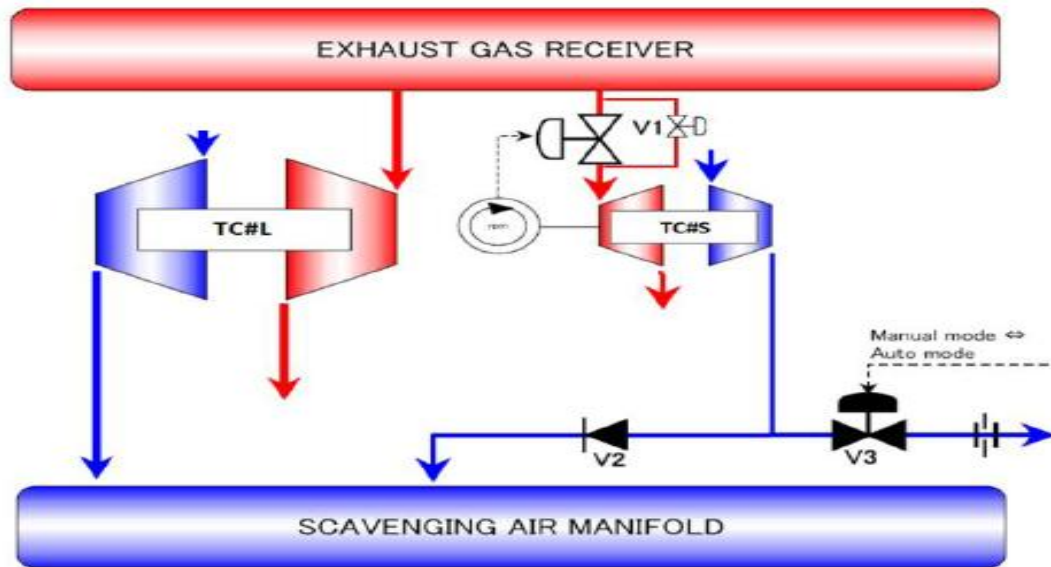
Figure 38. Low load layout sequential turbocharging[38]

6.6.1.1 <u>*Sequential Turbocharging:*</u>

- A secondary turbocharger of different size is added to the engine

- Control valves cut the smaller turbocharger in or out according to engine load

6.6.2 Auto tuning

Auto-tuning ensures that the combustion process of a MAN Diesel engine is always optimized. This allows for continuous adaptation to wear, changed fuel properties andoperating conditions. The result is a reduction of fuel consumption, CO_2 emissions and particulates. Today, tuning of the engine performance is a process done manually by the marine engineer. Typically, it takes some hours once a month or whenever required, e.g. after engine overhaul. The tuning will make the engine run safely within recommended load limits but still leaves a margin for performance optimization as operating conditions and fuel oil properties change over time. With Auto-tuning, this margin can be harvested by continuously and automatically tuning the engine for best performance, a task that is not feasible to be done manually.

6.6.2.1 *Constant measuring and tuning*

The Auto-tuning concept is based on online measurements of the combustion pressures in the cylinder chambers. This is an extremely harsh environment for a sensor to function in as the exhaust gas passes with high temperature and at high pressure. However, sensor technology has reached a point that allows for constant

measuring for more than 4 years of engine running. In comparison, a standard car engine will, in its lifetime, not run much more than a total of one year.

The developed engine control system constantly monitors and compares the measured combustion pressures to the reference value. Hereafter, the control system will automatically adjust the timing of the fuel injection in accordance with the deviation between the measured value and the reference value. This is done in order to reach the optimal combustion pressure during the next firings.

6.6.2.2 *Being in tune reduces fuel consumption*

The constant and automatic tuning to best engine performance allows for continuous

adaptation to wear, changed fuel oil properties and operating conditions, e.g. sailing in cold or warm climate. This offers a wide range of benefits namely reduction in fuel consumption, CO_2 emission and carbon particles, as well as reduced maintenance costs and risk of damage.

The reduction in fuel consumption for the average vessel is expected to be above 1%, whereas some vessels will have a potential of more than a 3% reduction.

Fuel Oil Consumption:

- Reduction potential: 3 g/kWh

- Reduction average: 1 g/kWh

Emission:

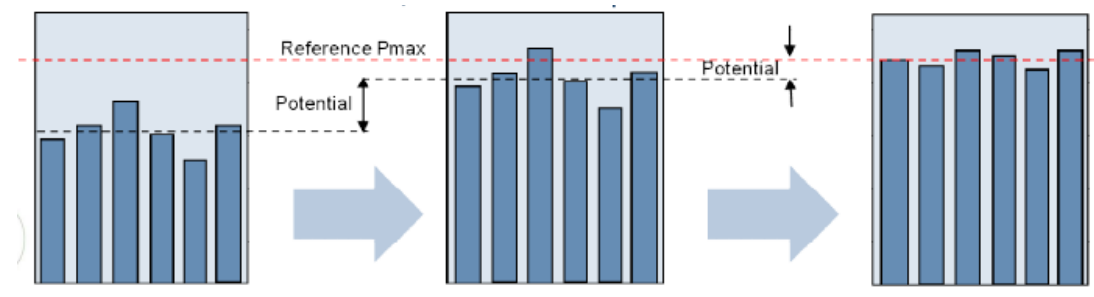- Potential: 2% CO2 reduction[28]

Figure 39. Pure Pmax level increase Potential 5-10bar At full as well as part loads[38]
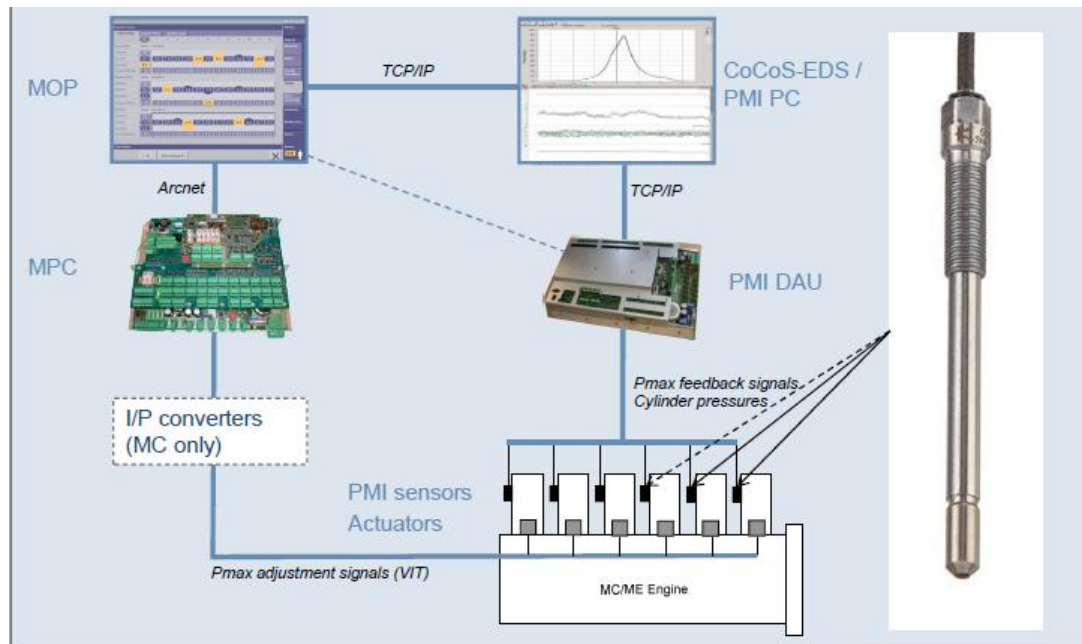
Figure 40. CO2 reduction auto tuning[38]

6.7 Other Abatement techniques

6.7.1 Intelligent (Camshaftless) Engines

The new electronically controlled camshaftless engines allow great flexibility for optimisation of the combustion process over the full range of operating conditions. Some of the features have been available on conventional engines with electronic control, but the camshaftless computer controlled engines have allowed greater operational flexibility. As far as NOx is concerned, the main features are computer control of variable injection timing (VIT), injection rate shaping, variable injection pressure and variable exhaust valve closing (VEC). Variable exhaust closing gives the ability to change the effective compression ratio. With VEC and VIT, it is possible to optimise the interplay of injection timing retard and increased compression ratio over the whole load range, to maintain peak pressures at low load while avoiding excessive peak pressures at high load. Common rail injection gives high injection pressures and thus good spray characteristics even at low loads.[14]

6.7.2 Injection Rate Shaping

Sulzer describe the use of different injection patterns in the RT-Flex common rail, slow speed engine , as illustrated in Figure 41. With pre-injection, a small part of the fuel charge is injected before the main charge. With triple injection (pulsed injection), the fuel charge is injected in separate, short sprays in succession. With sequential

injection, each of the three nozzles in a cylinder is actuated with different timing. For HFO, pulsed injection gave about 20% NOx reduction with about 7% increase in fuel consumption. Sequential and pre-injection gave less NOx reduction and less fuel consumption increase. The effects are the result of changes in the overall pressure development and interaction between fuel sprays. The NOx/fuel consumption trade-off is apparent.

Pre-injection can be used to shorten the delay period in medium speed engines and thus decrease temperature and pressure during the early stages of combustion, resulting in reduced NOx. Pre-injection can reduce particulates which are increased by other NOx control measures, thus allowing greater flexibility in NOx control. [14]
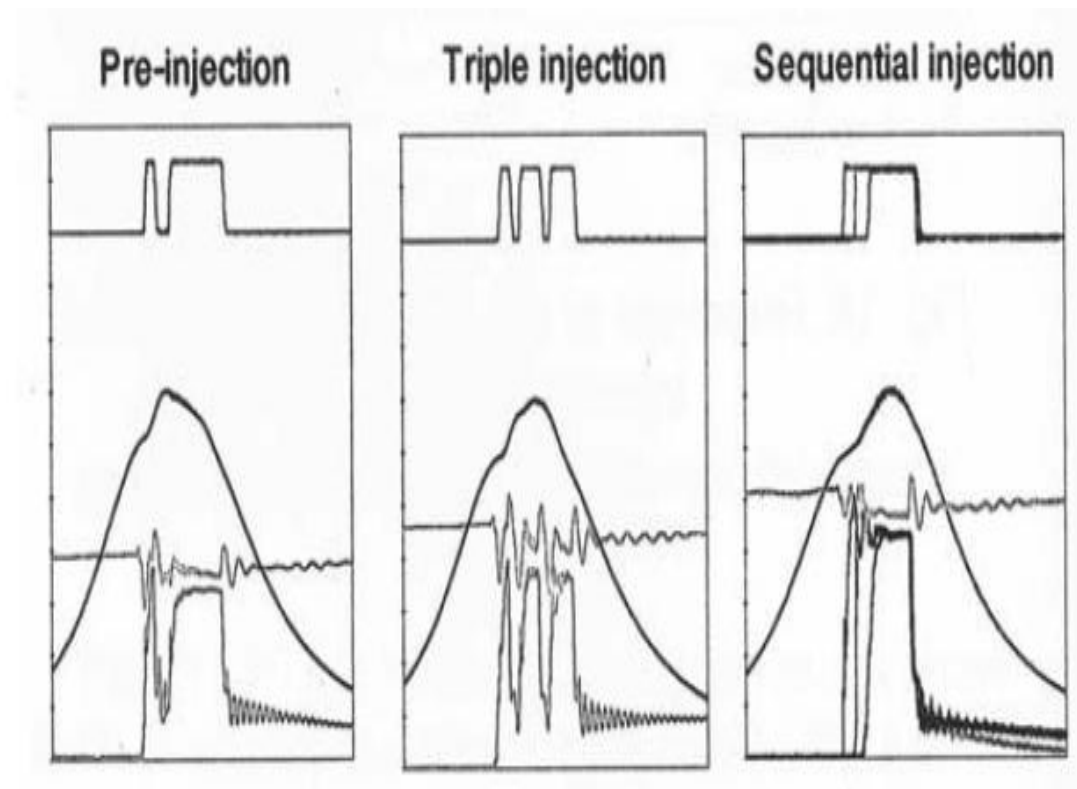
Figure 41. Injection Patterns for Sulzer RT-flex[14]

6.7.3 Lean NOx traps

Lean NOx traps are made of a honeycomb system that contains a precious metal such as platinum. The function of the precious metal is to oxidize the engine out NO to NOx. Another pivotal component of the LNT is an alkali metal salt that is used to form and store a nitrate during the common lean burn scenario of the diesel cycle. NOx is not easily oxidized in the O_2 rich environment. If the engine is run in a rich burn mode or secondary injection of fuel into the exhaust occurs, the nitrate releases

the NOx that is then reduced to N_2 and H_2O. Diesel engines run lean to produce their power, torque and efficiency. Therefore, in order for the LNT to work, an engine ECU or other controller must inject more fuel for a given time to create rich burn conditions allowing the oxidation of NO_2. This condition creates a fuel penalty. A study done on a 1.7L A170 engine at Argonne National Laboratory showed NOx conversion efficiency approximately 89 percent with a fuel penalty of just over 11 percent [29]. These numbers are promising for LNT technology but mainly for light duty applications as tested. A fuel penalty on the order of 10 percent would be too costly to implement in marine applications. LNTs are highly sensitive to the sulfur content of fuels. Conversion efficiency drops with both catalyst aging and increasing sulfur content.[29]

6.7.4   Hydrocarbon SCR

Hydrocarbon SCR (H-SCR) systems use a hydrocarbon fuel such as ethanol to reduce NOx emissions. This system requires a secondary injection system for the ethanol injection into the exhaust system. The catalyst is alumina supported, highly loaded with silver. At temperatures in the range from 350-400 ^{o}C, the ethanol quickly converts to acetaldehyde for NOx reduction. Conversion efficiencies for such systems have been as high as 80-90 percent. This system's fuel penalty is approximated at about two to three percent, significantly lower than the penalty for a LNT. A disadvantage of an H-SCR system is the increased HC emissions slipping past the catalyst. This problem is addressed with the use of catalyzed diesel particulate traps. Oakridge National Laboratories and Caterpillar conducted tests on a Cummins ISB 5.9 liter engine used in light duty trucks. The test showed NOx conversion efficiency as high as 95 percent. However, as catalyst core temperatures dropped to 250oC the converter efficiency fell to 25 percent. Further research must be done in the area of HC-SCR before it can reach the wide range of efficiencies achieved by urea SCR.[29]

6.7.5   Urea SCR

Selective catalytic reduction systems utilizing urea as a reducing agent are one of the most promising means of meeting the new stringent diesel emissions standards. When compared to other reduction methods, urea-SCR shows substantial NOx reduction and a wider operational temperature range. Urea SCR systems have been used on
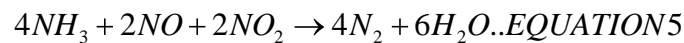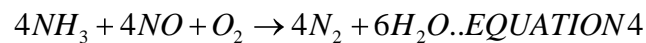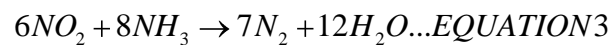
stationary power plant applications for years. This stationary technology now faces the challenge of becoming a mobile, transient application.

The main goal of the system is to reduce NOx by ammonia injection. SCR catalyst cores are made of mainly metal zeolite compounds. Research is also being done with combined catalysts. These compounds react with ammonia to convert NOx into N_2 and H_2O. The reducing agent solution is eutectic with 32.5 percent urea in water.

The ammonia needed for the reaction comes from the high temperature hydrolysis of urea with the exhaust flow. The equation for hydrolysis is given below and yields both ammonia (NH_3) and isocyanic acid (HCNO). The second equation shows the further reduction of HCNO with water vapor in the exhaust.

$$(NH_2)_2CO \rightarrow NH_3 + HCNO.......Equation 1$$
$$HNCO + H_2O \rightarrow NH_3 + CO_2...Equation 2$$
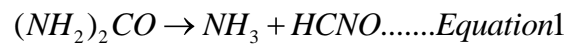
The majority of these systems utilize an upstream oxidation catalyst to optimize the NO_2 /NO ratios. Once this ratio is optimized, three main equations describe how the urea SCR works to reduce NOx. They are:

$$6NO_2 + 8NH_3 \rightarrow 7N_2 + 12H_2O...EQUATION 3$$
$$4NH_3 + 4NO + O_2 \rightarrow 4N_2 + 6H_2O..EQUATION 4$$
$$4NH_3 + 2NO + 2NO_2 \rightarrow 4N_2 + 6H_2O..EQUATION 5$$

As can be seen from the last equation, the NO_2/NO ratio is pivotal because this reaction occurs at a rate ten times faster than the second, converting as much NO as NO_2. Typically NO constitutes 90% of the NOx level while NO_2 is 10% or less. When hardware and control are properly sized and optimized urea SCR systems can achieve NOx reduction efficiencies greater than 90%. Therefore the physical design and implementation are important to ensure that the fundamental chemistry dominating a urea SCR system can occur.[29]

Reduction of particulate matter and gaseous emission from marine diesel engines using catalyzed particulate filter:

1. The exhaust gas temperature was significantly decreased, particularly at greater engine speeds, upon installing a catalyzed exhaust particulate filter in the tail pipe of a marine diesel engine.

2. Much lower carbon monoxide concentrations in the exhaust gas were observed with a catalyzed diesel exhaust particulate filter. The catalytic mixture consisted of platinum and rhodium group metals, coated on the filter surface, which presented a higher catalytic efficiency at higher exhaust gas temperatures under greater engine speeds. Therefore, a much lower CO concentration existed in the exhaust stream of the marine diesel engine installed with a catalyzed particulate filter at a greater engine speed.

3. The installation of the catalyzed diesel exhaust particulate filter resulted in a slight increase in nitrogen oxides at lower engine torque. However, the concentration of nitrogen oxides was abated at increasing engine speeds.

4. The smoke opacity of the exhaust gas was reduced substantially after a catalyzed diesel exhaust particulate filter was mounted in the exhaust stream system of a marine diesel engine. The smoke opacity readings were found to be nearly zero at various engine speeds.

5. The presence of a catalyzed particulate filter in the tail pipe of a marine diesel engine resulted in a slight increase in fuel consumption rate, bsfc and carbon dioxide concentration, while fuel conversion efficiency, air-to-fuel ratio and oxygen concentration were decreased.[30]
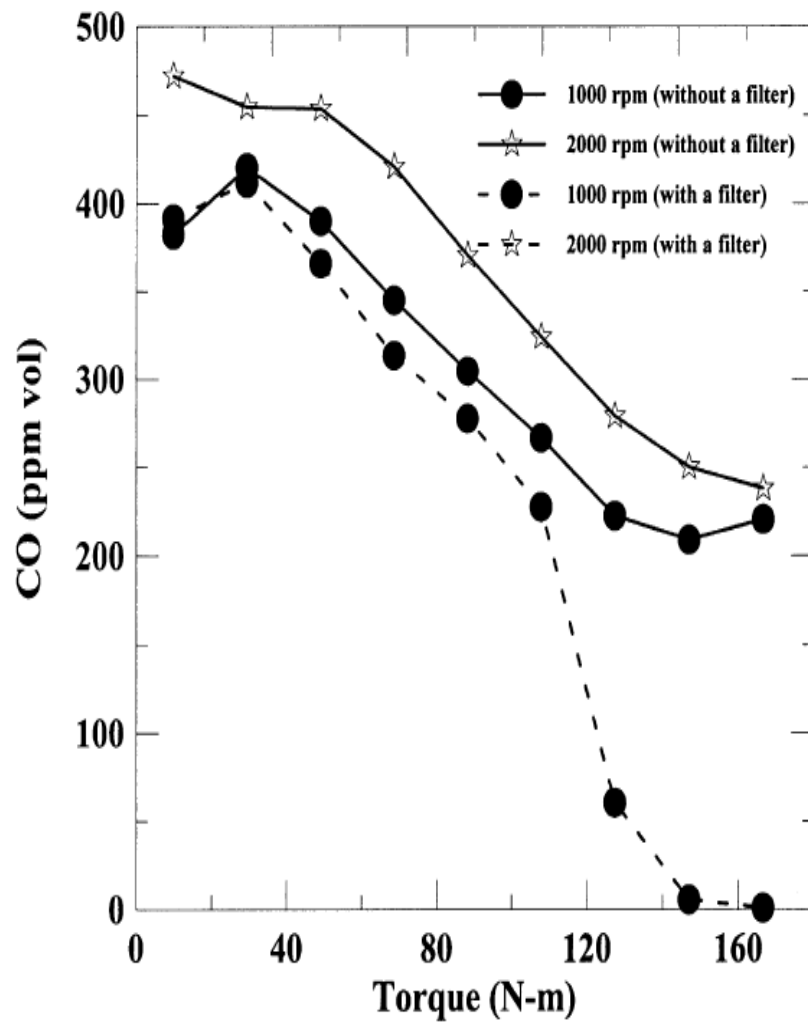
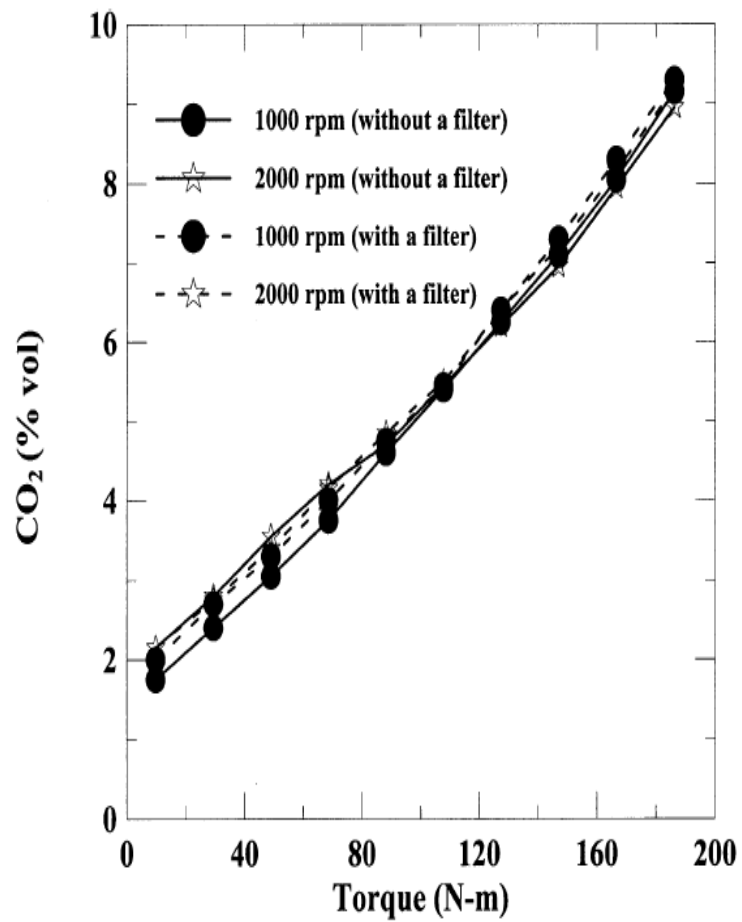*Figure 42. Effect of installing a catalyzed particulate filter on the CO emissions[30]*

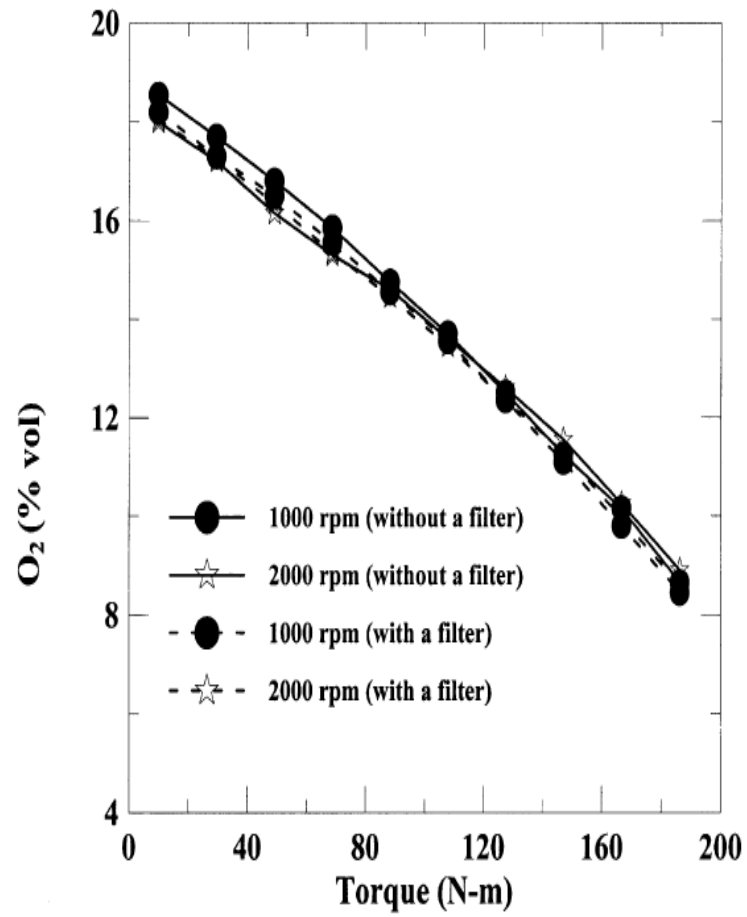*Figure 43. Effect of installing a catalyzed particulate filter on the CO2 emissions[30]*

Figure 44. Effect of installing a catalyzed particulate filter on the excess O2 emissions[30]
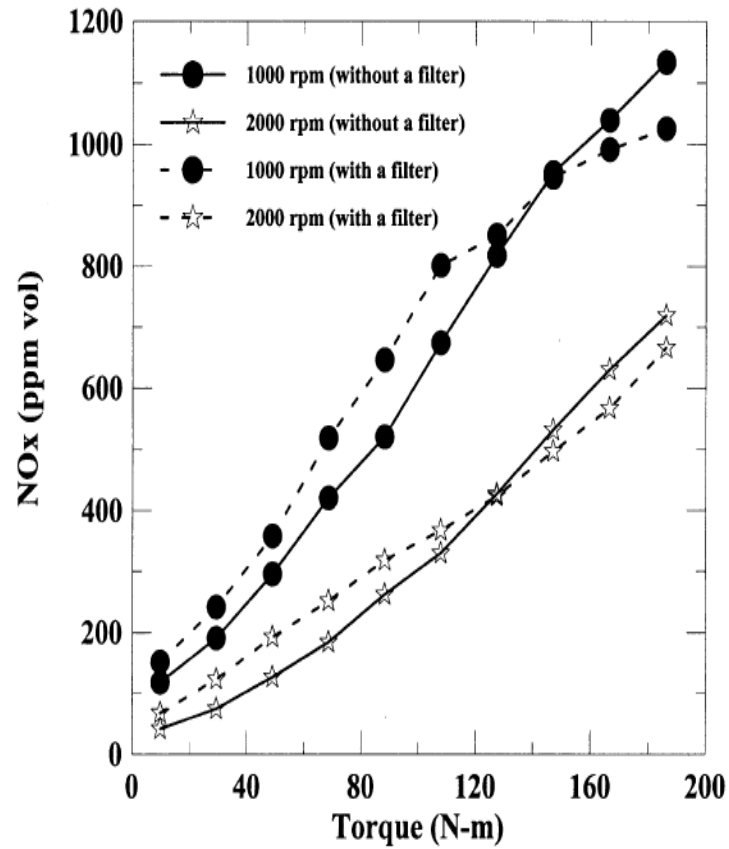
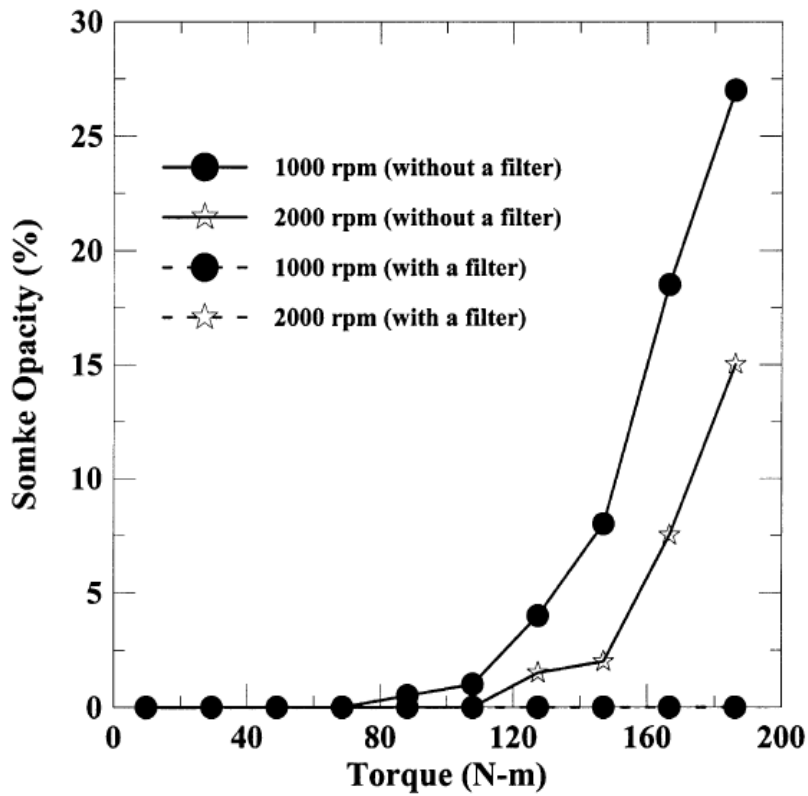*Figure 45. Effect of installing a catalyzed particulate filter on the NOX emissions[30]*

Figure 46. Effect of installing a catalyzed particulate filter on the smoke opacity[30]

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6.7.6 Krystallon seawater scrubber

The Krystallon seawater scrubber (SWS) removes 90-95 % of SO_2 and 10 - 20 % of NO_x. Additionally, the SWS removes 80 % of the particulates and 10-20% of hydrocarbons. The use of cyclone technology ensures that the particulate material is retained on board ship and not included with effluent overboard seawater. The particulate sludge is then deposited ashore along with shipboard oily waste according to local environmental and safety regulations. The system needs little extra space, as the majority of the system replaces existing exhaust silencers of the exhaust system. The accompanying positive side effects are the reduction of engine noise and a reduction of the diesel smell[31].

The Krystallon Scrubber works by bringing water in contact with hot exhaust gas. The exhaust gas is channeled through a concentric duct into a shallow water tank. Within the water, there are a set of mixing baffles which break up large gas flow into smaller bubbles, forcing the gas to come in contact with water, and thereby encouraging transfer of species from gas to water. The SO_x in exhaust gas is relatively soluble in seawater, so this transfer happens to a very high degree. Larger particles (greater than 2.5 micron) are predominantly captured in the water. Fine particles (smaller than 2.5 micron) may pass through without capture. Since the recirculated water is maintained at a pH of 2.0-4.0, this makes a very good medium for scrubbing of NO_x. Measurements have shown up to 20 % removal of NO_x, and this is enhanced due to the acidity of scrubbing liquor.[31]

6.7.7 Continuous water injection to charge air

Continuous water injection (CWI) to the charge air is a relatively simple method of reducing NO_X by up to 30% and PM emissions by about 25%, without engine modifications . A fine, freshwater mist is injected directly into the hot compressed air of the turbocharger outlet. CWI achieved a 22% reduction in NO_X and an average reduction in specific fuel consumption of 1%. CWI is not recommended at water-fuel ratios above 25% due to expected fuel consumption penalties. NO_X emissions reductions follow a negative exponential pattern with increasing water-fuel ratios. In Figure 47 the NO_X reductions are represented by the ratio of the controlled NO_X formation rate constant (K) to the uncontrolled NO_X formation rate constant (Ko).
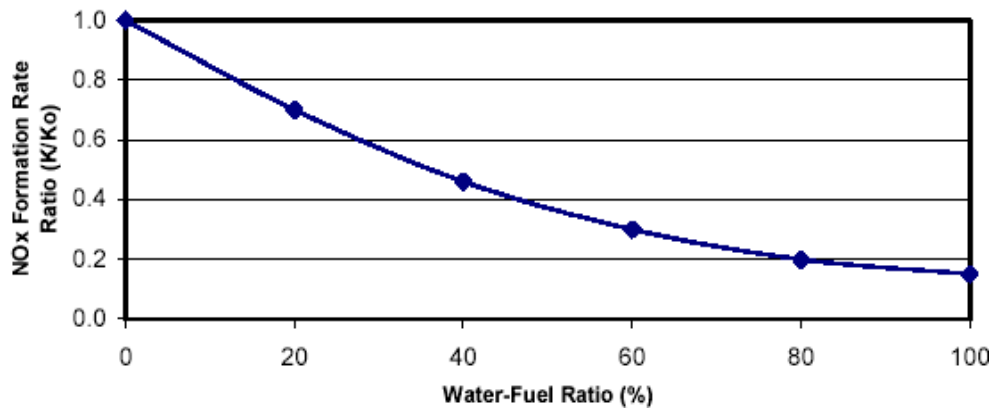
Figure 47. Theoretical NOX reductions for water injection[32]

The greatest NO_X reductions occur at the lowest water-fuel ratios (slope of line is high) and reductions diminish at higher ratios (slope is lower). At low water-fuel ratios (below about 25%), the presence of the water acts to improve the combustion kinetics, which results in a slight decrease in specific fuel consumption. However, above 25% water-fuel ratio, the water content starts to interfere with the combustion process and specific fuel consumption increases. Figure 48 shows that the optimum specific fuel consumption is theoretically achieved at a water-fuel ratio of approximately 10%, and that fuel penalties start occurring above 25%.
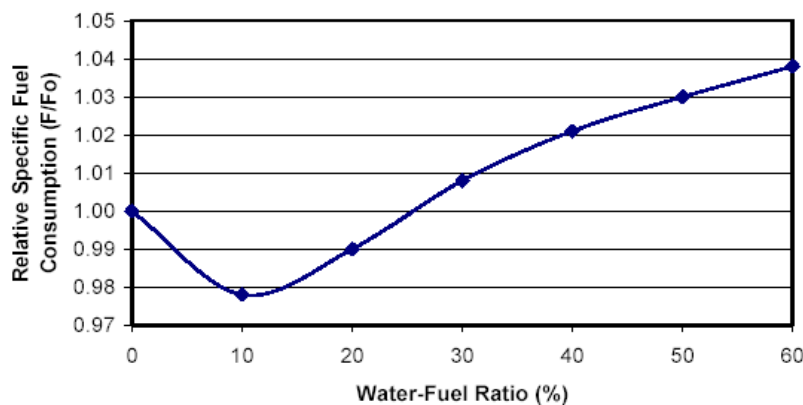

Figure 48. Fuel consumption effect of water injection[32]

6.7.7.1 *System description*

The CWI system consists of a water filtration and softener system, water pump, multiple fine-spray injectors, a process control system and a low-voltage power supply (see Fig. 49). The system is designed to operate at engine load levels above about 25-30% of MCR. Water is injected as a fine spray mist into the charge air manifolds directly after the turbocharger compressor on each engine at a pressure of 0,52MPa.
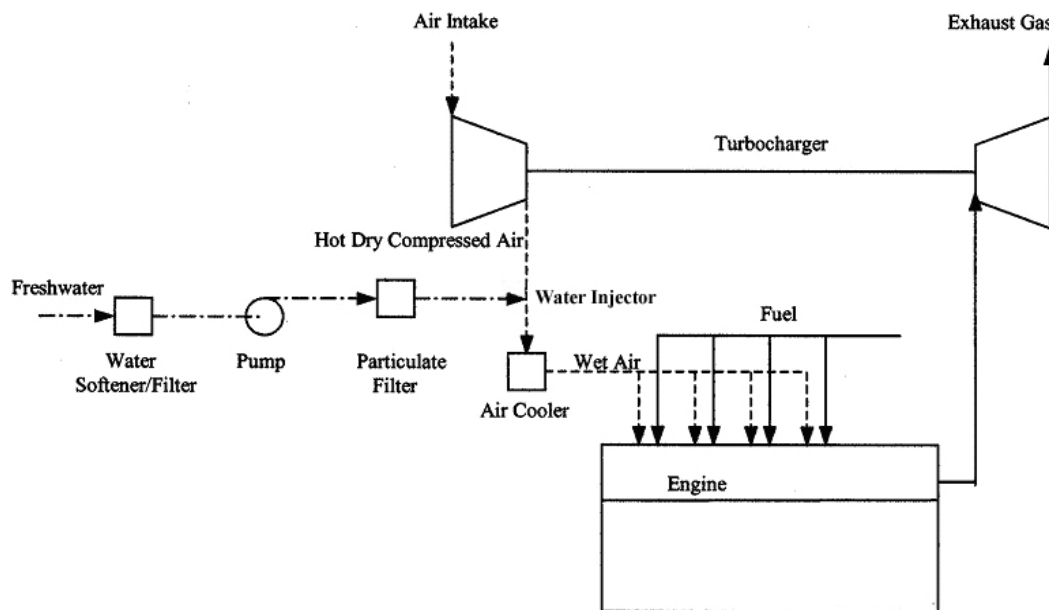
Figure 49. Continuous water injection system Schematic diagram[32]

The flow is controlled by solenoid valves on the water supply lines and is activated once certain threshold boost air temperature and boost air pressure levels are attained. The ship's freshwater system is assumed to be used as a source of water. A 24 V water pump with a dedicated power unit is used to boost the water pressure from about 0,41 MPa (standard pressure) to about 0,59 MPa. It is designed with an internal recirculation loop. The water filtration system is designed to demineralize water and remove foreign PM. It consists first of a softener cartridge on the suction side of the pump, followed by a particulate filter cartridge on the pump discharge. These cartridges must be changed monthly for good operation. Assuming a 20% water-fuel ratio is used at standard operating conditions, the freshwater system should have the capacity to handle approximately 25 additional tones of water for a 2½ day, one-way trip.[32]

6.7.8 Common rail

Common rail is a method to eliminate visible smoke from the exhaust, specially at low engine loads. Visible smoke generation is partly due to low injection pressure and striking of large fuel droplets on the hot surfaces during the combustion process. In this method, the fuel injection rate and injection pressure is controlled independently from the engine speed and load. Maintaining high pressure at lower loads prevents the formation of large fuel droplets during combustion and thus reduces visible smoke. Figure 50 shows the main components of the Wartsila common rail injection system

which is comprised of high pressure pumps, accumulators, fuel injection valves, and the control oil pumps. The high pressure pumps are camshaft driven and supply fuel to two engine cylinders. Each pump is connected to an accumulator and the accumulators are connected through double-walled pipes. Fuel is fed from the accumulators to the cylinders through the injection valves which are controlled by electro-hydraulic actuators. This set-up and design allows individual control of injection timing and duration for optimized injection at different engine loading conditions.

Figure 51 shows the effects of common rail on smoke emissions at different engine loads for a 2-stroke low speed engine. As can be seen, for engine loads less than 50%, common rail results in significant reductions in smoke emissions. [24]
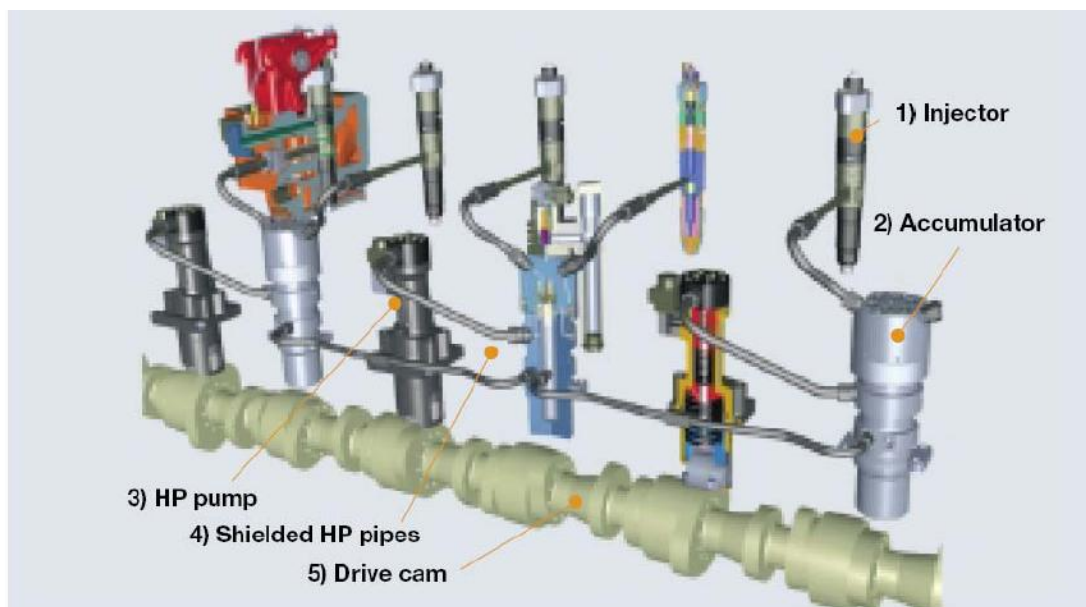

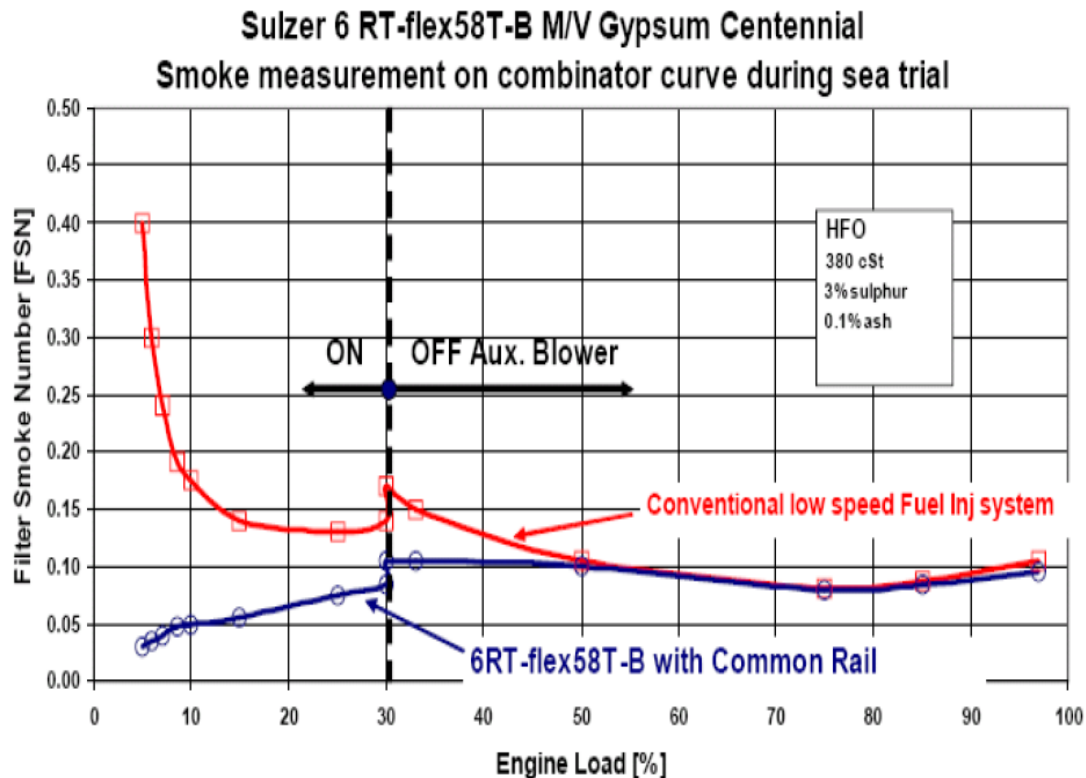*Figure50. Common rail components[24]*

Figure 51. Reducing visible smoke with common rail system for a 2 stroke engine[24]

6.7.9 Oxidation reactors

The oxidation reactors are used to convert CO and HC gases into CO_2 and H_2O. They also can remove a portion of PM that is associated with the soluble organic compounds (VOC). The catalyst has the potential to remove CO by more than 90 percent and HC by about 70 percent. The percent removal of PM associated with the VOC is dependent on the exhaust temperature and is usually between 50-90 percent. Oxidation catalysts are generally used in conjunction with the SCR systems to remove NO_x, CO, and HC. In this case, the oxidation catalyst is placed upstream of the SCR system. High sulfur fuel reduces the effectiveness of diesel oxidation catalyst and results in production of sulfate particles. There has not been any trials of using the oxidation catalyst on ocean going Vessels (OGVs).[24]
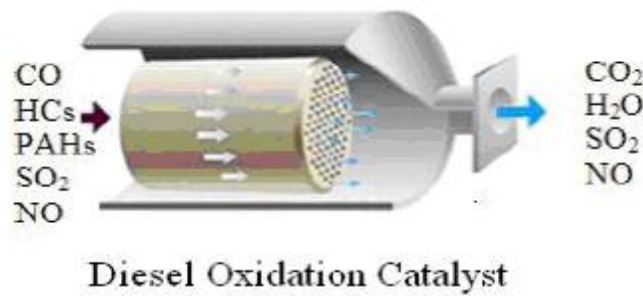
Figure 52. Diesel oxidation catalyst [24]

6.7.10 NOX absorber catalyst (NAC)

The NOx absorber catalysts use "base metal oxide" and precious metal coating to absorb NOx during engine lean operating conditions. When the maximum NOx storage condition is met, the catalyst goes through a regeneration process to release the NOx absorbed. Regeneration of the catalyst requires elimination of excess oxygen in the exhaust. This is accomplished with either running engine under rich operating condition for a short period of time or by injecting fuel upstream of the catalyst to absorb the excess oxygen and convert NOx to nitrogen.[24]

6.7.11 Biodiesel

Bio-diesels are renewable fuels that are extracted from animal fat and vegetable oils. The process includes reaction of oil and fat with methanol or ethanol to produce a lower viscosity fuel which has similar characteristics as diesel fuel. Pure biodiesel or B-100 can be used in diesel engines, but requires major engine modifications. A more common approach has been fuel blending with diesel fuel and 20% bio-diesel (B-20) which eliminates the need for engine modifications. Use of B-20 results in 10% reduction in CO and HC, 20% reduction in sulfate, and up to 15% reduction in PM. However, there will be some increase in NOx which can be up to 10%. There is a plan for expansion of bio-diesel capacity to 300 billion gallons annually in the U.S. and the current efforts to supports regulations that require 5% bio-diesel (B5) blend into the diesel fuel. Also there are plans to develop stand alone specifications for B6 through B20. There has not been any reported trial on using bio-diesel on marine engines.[24]

6.7.12 Reducing Greenhouse gas emissions from shipping

6.7.12.1 *Speed reduction*

Speed reduction is an operational measure which offers significant CO2 reductions. A 10% speed reduction gives 20+% reduction in fuel consumption over the same distance. Engines can be derated to optimise operation at reduced speeds by measures such as increasing compression ratio or turbocharger boost pressure to recover cylinder pressures when less fuel is injected per cycle. Classification Society Germanischer Lloyd have recently suggested that container ship speeds of 12 to 14 knots would be optimum. The present norm is 20+ knots. This reduced optimum speed would save fuel costs and emissions as well as absorbing overcapacity in the fleet.[9]

6.7.12.2 *Other measures*

Other measures include [9]:

- Alternative energy sources such as gas, wind, second/third generation biofuels (algae, lignocellulosic (e.g. from wood), pyrolysis oil, synthetic diesel, biomethane)

- Improved hull and propeller efficiency

- On-board energy efficiencies

- Weather routing

- New aftertreatment technologies, for example CSNOx by Ecospec, which is promoted to remove 74% of CO_2 from exhaust as well as 93% of SOx, 82% of NOx. It is not yet proven.

6.7.13 Combining water injection and EGR

Although DWI can be applied alone, it might be more interesting to apply it in combination with internal exhaust gas recirculation (EGR), as in WaCoReG (watercooled residual gas) by which we expect to obtain up to 70 per cent reduction in NOX emissions below the IMO limit. This would bring NO_X emissions down to about 5g/kWh. Internal recirculation normally increases the thermal load of the engine, so the water injection is applied to reduce temperature levels, thereby keeping thermal loads much the same as when running without internal EGR. With WaCoReG, the

water is injected earlier in the compression stroke than with DWI (Fig. 53). Exhaust gas recirculation reduces NOX formation at source by reducing the oxygen available in the engine cylinder and increasing the heat capacity of the cylinder charge. In contrast to four-stroke engines in which it is common practice to recirculate exhaust gases through external manifolds, in low-speed two-stroke engines we prefer to adapt the engine scavenging process to decrease the purity of gas in the cylinder at the start of compression. This is achieved by reducing the height of scavenge ports to reduce the scavenge air quantity flowing through the cylinder. One benefit is that smaller turbochargers are required for the reduced gas flows. The lower scavenge ports also have the benefit of allowing greater expansion in the cylinder and thus improving fuel consumption.[20]
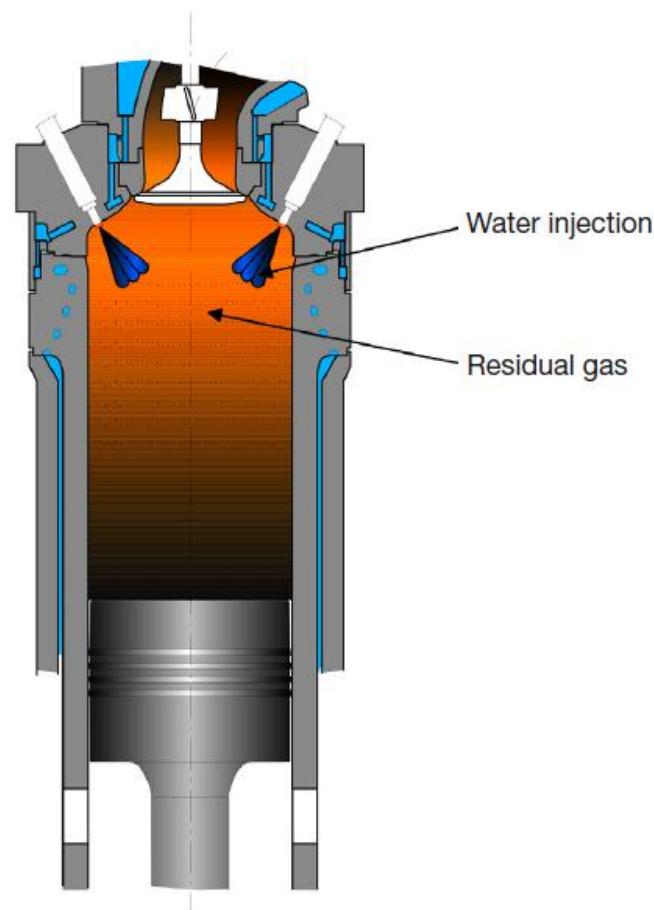

Figure 53. Principle of the WaCoReG process in which NOX formation is restrictedpartly by degrading the purity of the cylinder charge by increasing the residual gas content, and partly by direct water injection. The water is injected early in the compression stroke to cool the cylinder charge.[20]

6.7.14 Nonthermal Plasma assisted Catalytic reduction of NOx

To reduce NOx emissions from cargo ship engines, lighter distillate fuels can be used. However, the fuel cost is a big burden. After-treatment methods have some advantages. As presented previously, SCR technology can produce NOx reduction of 90% or more. One alternative to SCR under consideration is the use of a non-thermal plasma reactor and catalyst hybrid system where the reductant is a hydrocarbon for hydrocarbon designated plasma assisted catalytic reduction system. A potential advantage of the approach is that the fuel itself can be the reductant, thus removing the need for a urea infrastructure. Figure 54 shows a schematic diagram of the plasma assisted catalytic reduction of NOx.
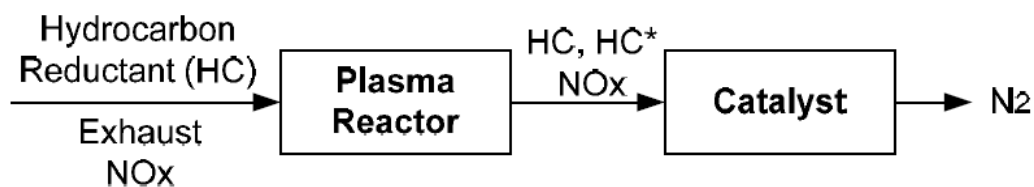

Figure 54. Plasma assisted Catalytic reduction of NOx [33]

Exhaust from an engine, containing NOx, hydrocarbon (HC) reductant is added before entering the non-thermal plasma reactor. Some hydrocarbons are partially oxidized in the plasma (HC*) and then the mixture is passed over a catalyst where the hydrocarbons promote the selective catalytic reduction of NOx to nitrogen. There are two general approaches:

1. The hydrocarbons are used to promote oxidation of NOx (primarily NO) to NO_2, and

2. A NO_2 selective catalyst is then used for the reduction to nitrogen. The reactions are shown in Equations 1-2.

$$Plasma + NO + HC + O_2 \rightarrow NO_2 + HC* + HC \quad (1)$$
$$Catalyst + NO_2 + HC + HC* \rightarrow N_2 + CO_2 + H_2O \quad (2)$$
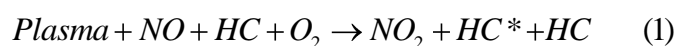
If particulates are present in the exhaust then the oxidation of the NO to NO_2 may be inhibited as the particulates may be oxidized by the radicals required for the oxidation of NO. In this case an NO selective catalyst may be more appropriate, as shown in Equations 3-4:

$$Plasma + HC + O_2 \rightarrow HC* + HC \qquad (3)$$
$$Catalyst + NO + HC + HC* \rightarrow N_2 + CO_2 + H_2O \quad (4)$$
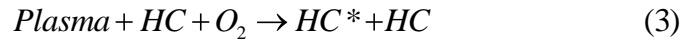
In both cases the presence of the hydrocarbons has two other important functions. The hydrocarbons minimize the production of acid products from the NOx, and minimize the oxidation of SO_2 in the exhaust (arising from the fuel sulfur), to SO_3. Operating the non-thermal plasma process can cause a fuel penalty for the engine. The plasma power and the hydrocarbon reductant are both derived from the fuel. The plasma power energy requirement is determined by the product of the specific energy and the exhaust gas flow rate.

The reductant concentration is determined by the HC:NOx ratio and the NOx flow rate in the exhaust. Thus the overall fuel penalty depends on the engine parameters. It is reported that a fuel penalty is in the order of 10% based on the present catalyst and plasma performance.[33]

6.7.15 Total heat recovery

In this concept, exhaust gas energy across the load range is increased by using a different turbocharger matching when engine air is drawn from the ambient air instead of from the engine-room. Usually marine engines are designed for intake temperatures of up to 45°C for tropical conditions with turbochargers drawing intake air from the engine room. If instead the intake air is drawn from outside the engine room thorough an air intake duct, the maximum intake temperature can be assumed to be no more than 35°C. The lower air intake temperature allows the turbochargers to be rematched in order to return the thermal load of the engine back down to what prevails for the intake temperature at 45°C. The thermal load of the adapted engine will then be no greater than that of the usual engine so as not to jeopardize engine reliability. The rematched turbochargers allow more exhaust gas to be branched off compared with the conventional tuning. Therefore the rematched system gives both an increased exhaust gas temperature for an exhaust gas economiser and an increased branched-off exhaust flow for an exhaust gas power turbine at ISO reference conditions [20].

Exhaust energy can thus be recovered and applied in both a steam turbine and exhaust-gas power turbine to generate electrical power, equivalent to about 11% of engine power (Figs. 55 and 56). The electrical power can be employed either in a shaft motor/generator or in supplying shipboard services. The generated power can

thus contribute significant savings in both fuel costs and exhaust emissions (CO_2, NOX, SOX, etc.). The payback time would depend upon the installation design and its operating costs, but would be expected to be less than five years.

The Total Heat Recovery Plant also offers an attractive possibility for powering the larger container ships which need more propulsion power than is available from the 14- cylinder Sulzer RT-flex96C engine. The standard engine gives an MCR power of 80,080 kW, thereby having a continuous service output (85% load) of 68,068 kW. At this engine rating, the Total Heat Recovery Plant would contribute a shaft power of 7390 kW. The combined service power for propulsion would therefore be 75,458 kW, equivalent to an engine MCR power of 88,770 kW for a plant without heat recovery [20].

Thus a single Sulzer 14RT-flex96C engine with a Total Heat Recovery Plant would be sufficient for the propulsion of single-screw container ships up to 12,000 TEU capacity. It thereby allows these larger ships to be powered by engines of well-established, proven design[20].
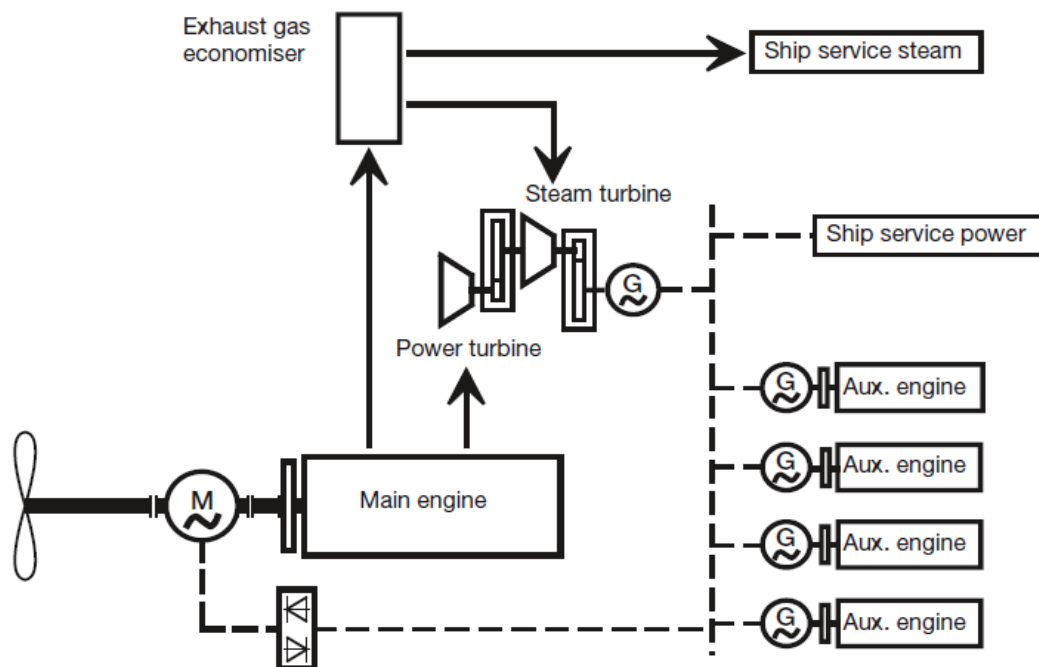

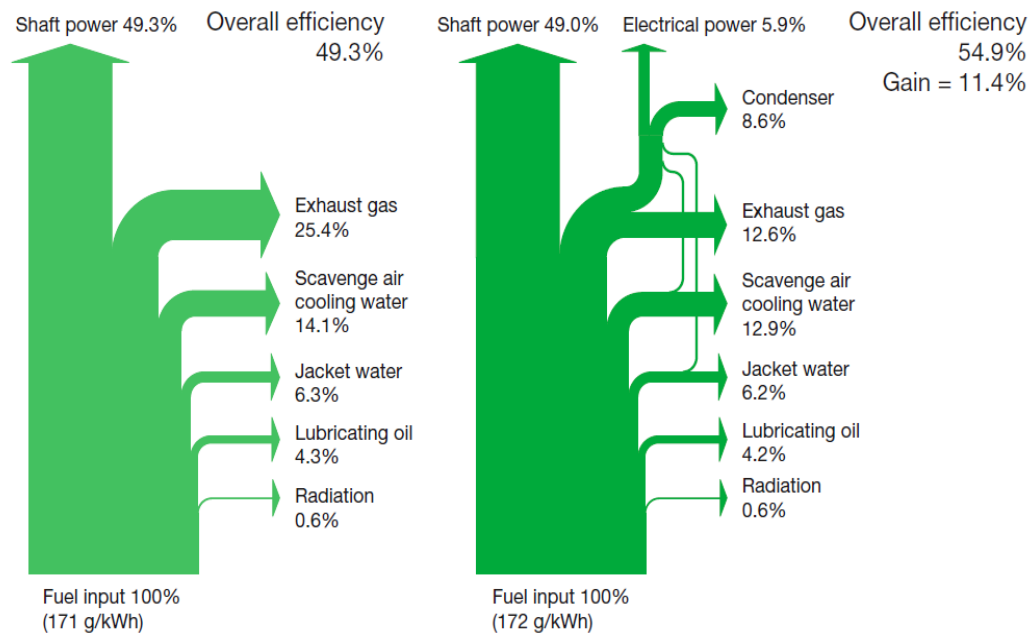*Figure 55. Schematic of the total heat recovery plant[20]*

Figure 56. Comparison of heat balances for Sulzer 12RT –flex 96C engines without heat recovery (left) and with total heat recovey (right)[20]

7 THE FUTURE

7.1 Green ship of the future

Green Ship of the Future is a unique cooperation in which companies across the Danish maritime industry join forces in order to develop strategies to reduce CO_2 by 30 %, SO_X by 90 %, NO_X by 90 % and particulate emissions from both existing ships and new buildings. Participation is open for all Danish companies and organisations that meet the condition of being able to demonstrate a technology for reduction of air emissions within one of the four focus areas: machinery, propulsion, operation and logistics.

Many elements are coming together with Green Ship of the Future: research, development, demonstration, innovation, education, training and dissemination of knowledge.

Many fields of knowledge are involved such as: systems for recycling heat energy, optimization of the hull, propellers and rudders, optimization of the draft and speed for a given route and arrival time and monitoring the fouling of hulls and propellers. Engine technology is an essential factor for achieving the planned benefits.

In July 2009, Green Ship of the Future received the International Environmental Award from the Sustainable Shipping organisation for being the most environmentally friendly shipping initiative. Since its foundation, Green Ship of the Future has experienced great success. From the starting point with four project partners, the group of companies has expanded dramatically and today consists of 23 dedicated project partners. The typical partner has its main business within the maritime industry, but also universities, interest groups and national authorities support Green Ship of the Future.

In conclusion green ship:

Provide technology to obtain:

- 30% reduction of CO_2

- 90% reduction of SOx

- 90% reduction of NOx

To meet the reduction targets, the following four main areas are considered:

- Machinery WHR, scrubbers, EGR, etc.

- Propulsion Propellers, rudders, trim optimization, etc.

- Operations Route planning, performance monitoring, etc.

- Logistics better interaction between transport forms, development/modification of existing ship types etc.

The challenge was to take an existing modern design and evaluate the technologies suitable and to generate a picture of the improved performance of the vessel.

Main Conclusions from Concept

- With respect to NOx and SOx it is possible to reach the goals.

- Reducing NOx and SOx will in some cases cost increased CO2 emission.

- With respect to CO_2 we still need to work with technical solutions and operation to meet goal.

- Further reduction in CO_2 must be obtained through continued efforts to reduce vessel resistance, optimised operation (slow steaming), more effective propulsion systems, more fuel efficient engines, alternative fuel (LNG, Biofuel etc.) and addition of alternative green means of propulsion (fuel cells, wind, solar etc.) etc.

- Further reductions in CO_2 will also reduce NOx and SOx emissions.[34]

8 CONCLUSIONS

In this issue we examine the formation of pollutants in marine diesel engines and the international environmental legislation applicable for emission limits of these engines.

Furthermore emphasis is given on emissions abatement techniques inside the engine and the corresponding abatement applied in engine exhaust. A detailed literature review and the evaluation of published theoretical and experimental results led to the formulation of the following conclusions regarding internal procedure:

- The direct water injection (DWI) at a rate of 70% leads to a reduction of NO_x by 50% compared with conventional operation.

- Internal engine modifications leads to a reduction of NO_x by 20-30%

- 28% Engine gas recirculation leads to 69% reduction of NO_x

- Inlet air Humidification leads to 65-70% reduction fo NO_x

- Water fuel emulsion: each 10% water added leads to 10% further NO_x reduction

Respectively, relating to the use of external measures:

- Selective Catalytic reduction: at a 450^0C exhaust temperature, there is a $30\% NO_x$ reduction. The NO_x reduction with this technique could reach up to 90%.

- SO_x abatement techniques such as Sea water scrubbers, can achieve 75% SO_x reduction

- Finally, fuel switching can achieve 44-81% SOx reduction.

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