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EXHAUST EMISSIONS AND CONTROL FOR NAVAL ENGINES

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Abstract: *The global approach to NOx emission controls was taken by the IMO whose Annex VI (Regulations for the Prevention of Air Pollution from Ships) to Marpol 73/78 was adopted at a diplomatic conference in 1997. Ships burning marine diesel oil and heavy fuel oil at that time were reportedly responsible for around 7 per cent of global NOx emissions, around 4 per cent of global sulphur dioxide emissions and 2 per cent of global carbon dioxide emissions*

Key words: *emissions, NOx, oil, dioxide, sulphur*

1. Introduction

Marine engine designers in recent years have had to address the challenge of tightening controls on noxious exhaust gas emissions imposed by regional, national and international authorities responding to concern over atmospheric pollution. Exhaust gas emissions from marine diesel engines largely comprise nitrogen, oxygen, carbon dioxide and water vapour, with smaller quantities of carbon monoxide, oxides of sulphur and nitrogen, partially reacted and non-combusted hydrocarbons and particulate material.

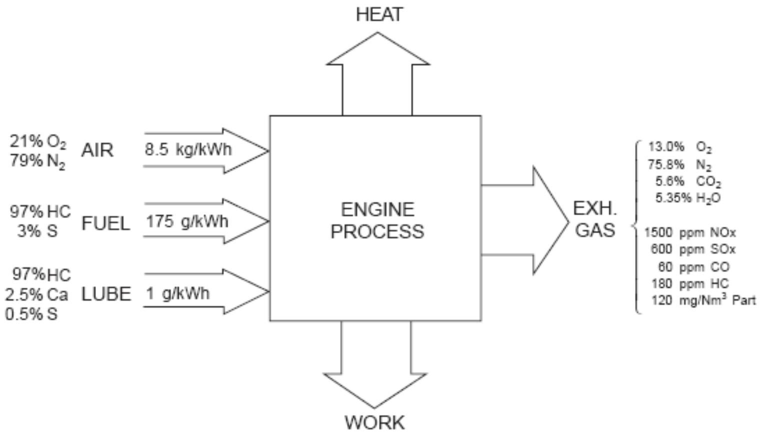

Fig. 1. *Typical exhaust emissions from a modern low speed diesel engine*

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2. The Pollutants

Nitrogen oxides (*NO*x), generated thermally from nitrogen and oxygen at high combustion temperatures in the cylinder, are of special concern since they are believed to be carcinogenic and contribute to photochemical smog formation over cities and acid rain (and hence excess acidification of the soil). Internal combustion engines primarily generate nitrogen oxide but less than 10 per cent of that oxidizes to nitrogen dioxide the moment it escapes as exhaust gas.

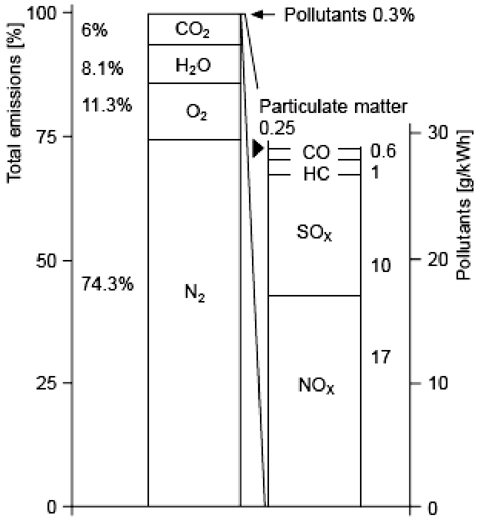


Fig. 2. *Typical composition of the exhaust gas products of a medium speed diesel engine*

Some 6 per cent of the total emission is carbon dioxide, with the 'real' pollutants representing only a 0.3 per cent share

Sulphur oxides (*SO*x), produced by oxidation of the sulphur in the fuel have an unpleasant odour, irritate the mucus membrane and are a major source of acid rain (reacting with water to form sulphurous acid). Acid deposition is a trans-boundary pollution problem: once emitted, *SO*x can be carried over hundreds of miles in the atmosphere before being deposited in lakes and streams, reducing their alkalinity.

Sulphur deposition can also lead to increased sulphate levels in soils, fostering the formation of insoluble aluminium phosphates which can cause a phosphorous deficiency. Groundwater acidification has been observed in many areas of Europe; this can lead to corrosion of drinking water supply systems and health hazards due to dissolved metals in those systems. Forest soils can also become contaminated with higher than normal levels of toxic metals, and historic buildings and monuments damaged.

Hydrocarbons (*HC*), created by the incomplete combustion of fuel and lube oil, and the evaporation of fuel, have an unpleasant odour, are partially carcinogenic, smog forming and irritate the mucus membrane (emissions, however, are typically low for modern diesel engines.)

Carbon monoxide (*CO*), resulting from incomplete combustion due to a local shortage of air and the dissociation of carbon dioxide - is highly toxic but only in high concentrations. Particulate matter (PM) is a complex mixture of inorganic and organic compounds resulting from incomplete combustion, partly unburned lube oil, thermal splitting of HC from the fuel and lube oil, ash in the fuel and lube oil, sulphates and water. More than half of the total particulate mass is soot (inorganic carbonaceous particles), whose visible evidence is smoke.

Soot particles (unburned elemental carbon) are not themselves toxic but they can cause the build-up of aqueous hydrocarbons, and some of them are believed to be carcinogens. Particulates constitute no more than around 0.003 per cent of the engine exhaust gases. Noxious emissions amount to 0.25-0.4 per cent by volume of the exhaust gas, depending on the amount of sulphur in the fuel and its lower heat value, and the engine type, speed and efficiency. Some idea of the actual pollutants generated is provided by MAN B&W Diesel, which cites an 18 V 48/60 medium speed engine in *NO*x-optimized form running at full load on a typical heavy fuel oil with 4 per cent sulphur content. A total of approximately 460 kg of harmful compounds are emitted per hour out of around 136 tonnes of exhaust gas mass per hour. Of the 0.35 per cent of the exhaust gas formed by pollutants, *NO*x contributes 0.17 per cent, sulphur dioxide 0.15 per cent, hydrocarbons 0.02 per cent, carbon monoxide 0.007 per cent and soot/ash 0.003 per cent.

Carbon dioxide: some 6 per cent of the exhaust gas emissions from this engine is carbon dioxide. Although not itself toxic, carbon dioxide contributes to the greenhouse effect (global warming) and hence to changes in the Earth's atmosphere. The gas is an inevitable product of combustion of all fossil fuels, but emissions from diesel engines—thanks to their thermal efficiency, are the lowest of all heat engines. A lower fuel consumption translates to reduced carbon dioxide emissions since the amount produced is directly proportional to the volume of fuel used, and therefore to the engine or plant efficiency. As a rough guide, burning one tone of diesel fuel produces approximately three tones of carbon dioxide. International concern over the atmospheric effect of carbon dioxide has stimulated measures and plans to curb the growth of such emissions, and the marine industry must be prepared for future legislation. (A switch from other transport modes: air, road and rail, to shipping would nevertheless yield a substantial overall reduction in emissions of the greenhouse gas because of the higher efficiency of diesel engines.)

The scope for improvement by raising the already high efficiency level of modern diesel engines is limited and other routes have to be pursued: operating the engines at a fuel-saving service point; using marine diesel oil or gas oil instead of low sulphur heavy fuel oil;

Adopting diesel-electric propulsion (the engines can be run continuously at the highest efficiency); or exploiting a diesel combined cycle incorporating a steam turbine. The steam-injected diesel engine is also promising.

Compared with land-based power installations, fuel burned by much of shipping has a very high sulphur content (up to 4.5 per cent and more) and contributes significantly to the overall amount of global sulphur oxide emissions at sea and in port areas. Studies on sulphur pollution showed that in 1990 *SO*x emissions from ships contributed around 4 per cent to the total in Europe. In 2001 such emissions represented around 12 per cent of the total and could rise to as high as 18 per cent by 2010.

*SO*x emissions in diesel engine exhaust gas, which mostly comprise sulphur dioxide with a small amount of sulphur trioxide - are a function of the amount of sulphur in the fuel and cannot be controlled by the combustion process.

If the fuel contains 3 per cent sulphur, for example, the volume of *SO*x generated is around 64 kg per tonne of fuel burned; if fuel with a 1 per cent sulphur content is used *SO*x emissions amount to around 21 kg per tonne of fuel burned. Chemical and washing/scrubbing desulphurization processes can remove *SO*x from the exhaust gases but are complex, bulky and expensive for shipboard applications, and increase overall maintenance costs. The most economical and simplest approach is thus to burn bunkers with a low sulphur content. (If a selective catalytic reduction system is installed to achieve the lowest *NO*x emission levels - see section below - then low sulphur fuels are dictated anyway to avoid premature fouling of the system's catalyst package.)

A global heavy fuel oil sulphur content cap of 4.5 per cent and a 1.5 per cent fuel sulphur limit in certain designated Sulphur Emissions Control Areas (SECAs), such as the Baltic Sea, North Sea and English Channel, is sought by the International Maritime Organisation (IMO) to reduce SOx pollution at sea and in port. The European Union strategy for controlling air pollution calls for all ships in EU ports to burn fuel with a maximum sulphur content of 0.2 per cent, which would force uni-fuel ships to carry low sulphur fuel specifically for this purpose. (See also the Fuels and Lubes chapter.)

3. Controlling *NO*x Emissions

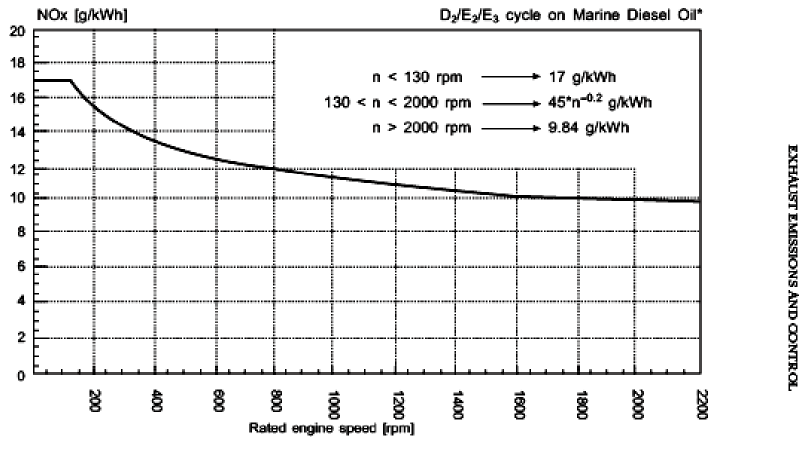
The global approach to *NO*x emission controls was taken by the IMO whose Annex VI (Regulations for the Prevention of Air Pollution from Ships) to Marpol 73/78 was adopted at a diplomatic conference in 1997. Ships burning marine diesel oil and heavy fuel oil at that time were reportedly responsible for around 7 per cent of global NOx emissions, around 4 per cent of global sulphur dioxide emissions and 2 per cent of global carbon dioxide emissions.

Annex VI entered into force 12 months after the date on which not less than 15 states, together constituting not less than 50 per cent of the gross tonnage of the world's merchant fleet, have ratified it. Ships constructed after 1 January 2000 (date of keel laying) were nevertheless required to comply.

The annex addresses engines with a power output of more than 130 kW installed in new ships constructed from that date and engines in existing ships that undergo a major modification.

Engines have to fulfil the *NO*x emission limits set by the IMO curve, which is related to engine speed. To show compliance, an engine has to be certified according to the *NO*x Technical Code and delivered with an EIAPP (Engine International Air Pollution Prevention) letter of compliance. The certification process includes *NO*x measurement for the engine type concerned, stamping of components that affect *NO*x formation and a Technical File that is delivered with the engine. IMO's current maximum allowable NOx emission levels depend on the speed category of the engine and range from 17 g/kWh for engines of speed <130 rev/min to 9.84 g/kWh for engines of speed >2000 rev/min. Much tougher curbs on *NO*x and other emissions are set by regional authorities such as California's Air Resources Board; and Sweden has introduced a system of differentiated port and fairway dues making ships with higher *NO*x emissions pay higher fees than more environment-friendly tonnage of a similar size.

With stricter controls planned by the IMO, the reduction of *NO*x emissions remains a priority for engine designers whose concern is to secure environmental acceptability without compromising the impressive gains in engine fuel economy and reliability achieved in recent years. (Advances in thermal efficiency have, ironically, directly contributed to a rise in *NO*x emissions) Considerable progress has been made and is projected.



* Testcycles in accordance with ISO 8178 Part 4

Fig. 3. *Maximum allowable NOx emissions for marine diesel engines* (IMO)

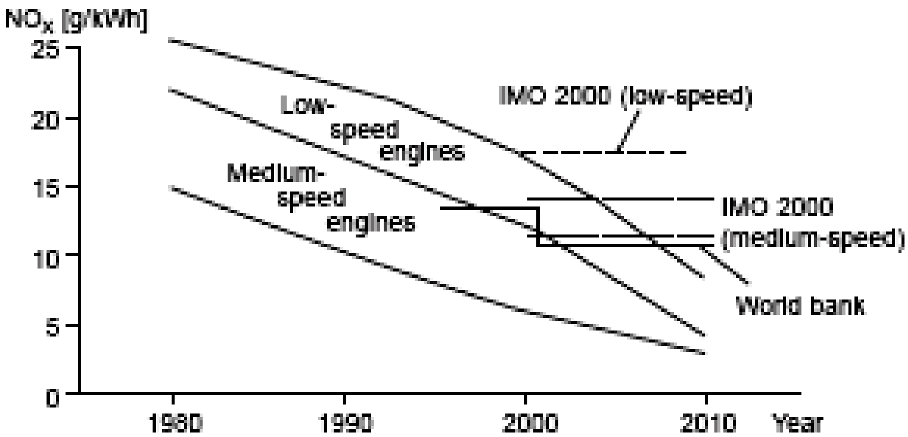


Fig. 4. *NOx emission trends for typical two-stroke and four-stroke diesel engines compared with* IMO *requirements (Wärtsilä)*

Dominating influences in the formation of *NO*x are temperature and oxygen concentration: the higher the temperature and the higher the residence time at high temperature in the cylinder, the greater the amount of thermal *NO*x that will be created. A longer combustion timespan means that low speed two-stroke engines therefore generate higher *NO*x emissions than medium and high speed four-stroke engines of equivalent output. Apart from the use of alternative fuels, such as methanol, two main approaches can be pursued in reducing *NO*x emission levels: Primary (in-engine) measures aimed at reducing the amount of *NO*x formed during combustion by optimizing engine parameters with respect to emissions (valve timing, fuel injection and turbocharging). Emission levels can be reduced by 30–60 per cent. Secondary measures designed to remove *NO*x from the exhaust gas by downstream cleaning techniques. Emission reductions of over 95 per cent can be achieved.

De-*NO*x technology options are summarized in Figure 5.

The primary *NO*x reduction measures can be categorised as follows:

- Water addition: either by direct injection into the cylinder or by emulsified fuel.
- Altered fuel injection: retarded injection; rate-modulated injection;
- *NO*x-optimized fuel spray pattern.
- Combustion air treatment: Miller supercharging; turbocooling; intake air humidification; exhaust gas recirculation; and selective non-catalytic reduction. (Miller supercharging and turbocooling are covered in the Pressure Charging chapter.)
- Change of engine process: compression ratio; and boost pressure. The basic aim of most of these measures is to lower the maximum temperature in the cylinder since this result is inherently combined with a lower *NO*x emission.

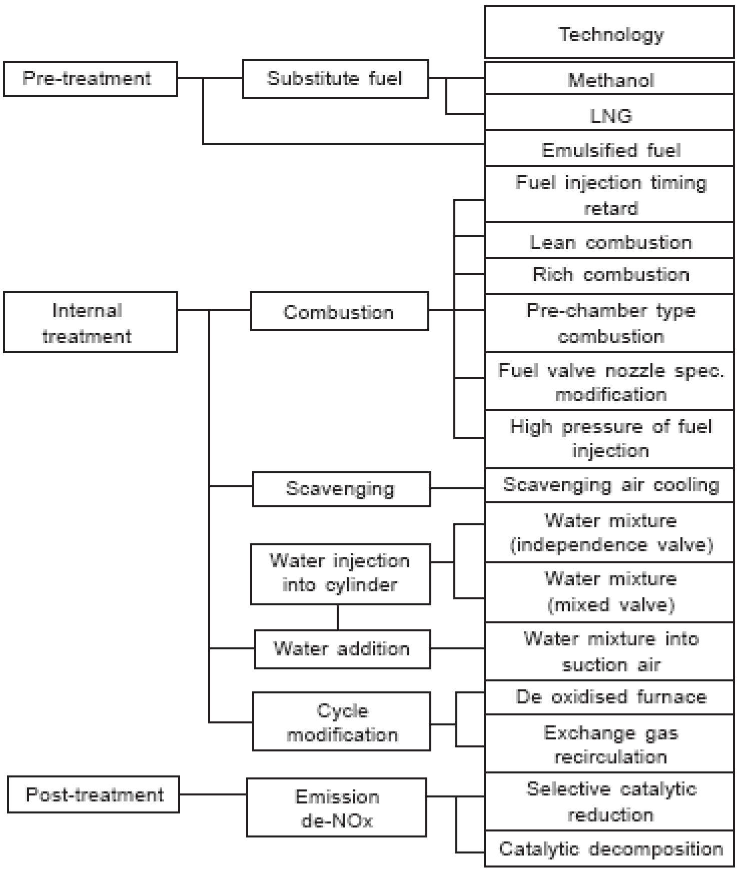


Fig. 5. *Methods of reducing NOx emissions from marine diesel engines (Mitsubishi Heavy Industries)*

New generations of medium speed engines with longer strokes, higher compression ratios and increased firing pressures addressed the *NO*x emission challenge (Figure 6).

The low *NO*x combustion system exploited by Wärtsilä throughout its medium speed engine programme, for example, is based on an optimized combination of compression ratio, injection timing and injection rate.

The engine parameters affecting the combustion process are manipulated to secure a higher cylinder pressure by increasing the compression ratio. The fuel injection equipment is optimized for late injection with a short and distinct injection period. *NO*x reductions of up to 50 per cent are reported without compromising thermal efficiency, achieving an *NO*x rate of 5–8 g/kWh compared with the 15 g/kWh of a typical conventional engine with virtually no effect on fuel consumption.

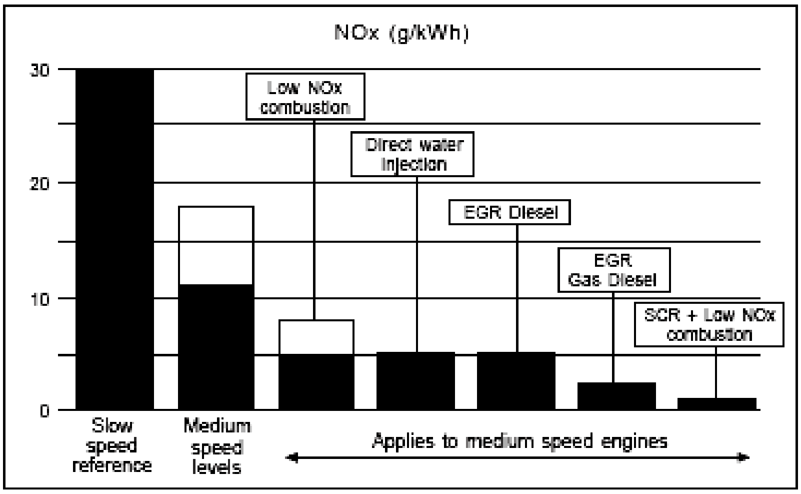


Fig. 6. *Emission control measures and their potentials in reducing NOx output. EGR = exhaust gas recirculation; SCR = selective catalytic reduction (Wärtsilä Diesel)*

Low *NO*x combustion is based on:

- A higher combustion air temperature at the start of injection, which significantly reduces the ignition delay.
- A late start of injection and shorter injection duration to place combustion at the optimum point of the cycle with respect to efficiency.
- Improved fuel atomization and matching of combustion space with fuel sprays to facilitate air and fuel mixing.

Some Wärtsilä Vasa 32 engines were equipped with a “California button” to meet the US regional authority’s strict *NO*x control. A planetary gear device allows the necessary small injection timing retard to be effected temporarily while the engine is running when the ship enters the Californian waters.

4. Conclusion

Summing up the various options for noxious exhaust emission reduction, Wärtsilä suggests:

-The first choice is engine tuning modifications that can achieve up to 39 per cent reductions in *NO*x emission levels compared with those of standard engines in 1990.

-For further *NO*x reductions, separate water injection is considered the most appropriate solution; the technique has proved its ability on the testbed to reduce emission levels by some 60 per cent compared with today’s standard engines.

- Exhaust gas after-treatment by selective catalytic reduction (SCR) has proved an effective solution in reducing *NO*x by 90 per cent or more, despite the special difficulties imposed by using high sulphur fuel oils;

- Requirements for lower emissions of sulphur oxides (SOx) are most favourably met by using fuel oils with reduced sulphur
- contents. although SOx reduction by exhaust gas after-treatment is technically feasible, the de-sulphurization process inevitably imposes a disposal problem which would not be acceptable for shipping.
- Carbon monoxide and hydrocarbons can, if necessary, be reduced by an oxidation catalyst housed within an SCR reactor.
- -Particulates reduction, with the engine running on heavy fuel, poses a challenge. Technical solutions are available (electrostatic precipitators, for example) but involve either great space requirements or great expense. Particulate emissions are reduced by 50–90 per cent, however, through a switch to distillate fuel oils.

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References

1. Anastase, P: *Instalații energetice navale*. Constanța. Ed. Muntenia & Leda, 2000.
2. Dragalina, A.: *Motoare cu ardere internă,* Vol. 2. Constanța. Ed. Academiei Navale "Mircea cel Bătrân", 2003.
3. Dragalina, A.: *Calculul termic al motoarelor diesel navale*. Constanța. Ed. Muntenia & Leda, 2002.
4. Ristea, M.: *Evoluția parametrilor geometrici şi funcționali ai motoarelor cu ardere internă utilizate în domeniul naval. Raport de cercetare ştiințifică*. Academia Tehnica Militara, Bucuresti, 2008.
5. Ristea, M: *Stabilirea unor modele de calcul pentru determinarea parametrilor funcționali, în funcție de raportul de comprimare*. *Raport de cercetare ştiințifică.* Bucuresti. Academia Tehnică Militară.
6. Ristea, M., Pruiu, A.: *Reducerea conținutului de noxe la motoarele diesel.* In: *Conferința internațională NAV – MAR EDU 2007, secțiunea II, Constanța 15 – 17 Noiembrie 2007*, *** *Termotehnica*. Anul VII, Nr.1-2/2003. Revista Societății Române a Termotehnicienilor.