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Methods of Reducing Emissions from Two-stroke low-speed Diesel Engines

The worldwide focus on fuels is generally increasing because of the focus on exhaust gas emissions. General awareness of environmental issues is increasing rapidly. Diesel engine makers were first involved in questions regarding exhaust gas emissions in the field of stationary applications. A study of the exhaust gas emissions from a diesel engine represents a challenge to both the engine designer and to makers of exhaust gas treatment equipment. It is also a valuable tool for reaching a deeper understanding of the engine combustion process. These emissions control technologies, like Selective Catalytic Reduction (SCR), will help to reduce pollutants that impact our health and the health of our communities as well as reduce smog creation and other factors that contribute to climate change and global warming.

Keywords: *emissions, SCR, IMO proposal*

1. Introduction

When talking about exhaust gas emissions from ships, the relevant components are NOx, SOx, CO, CO2, HC, and particulates, see Figure 1. So far, particulates and HC, together with NO2 and water vapour (constituting visible smoke) are being judged by not so accurate opacity measurements. At this stage, and probably for many years ahead, NOx and SOx will be the only components that will be given international measurable limits in the marine market. It is expected that HC and particulates will follow, but it is uncertain when this will happen.

The industry is still considering the optimum methods of controlling HC and particulates, and the method of measuring also remains to be agreed upon. The situation is different for power plants, for which there are often limits to all polluting components of the diesel exhaust gas.

It should be noted that pollutants are usually measured as concentrations, whereas rules are formulated as absolute emission factors (mass per unit, time or power) arrived at by calculation, based on the concentration measurements.

Over the years, MAN B&W has worked with the exhaust gas emission issue in order to develop means to reduce the levels so as to comply with limitations which can be expected to come.

In the following, each exhaust gas component will be described.

Oxygen. Low speed, two-stroke, crosshead diesels operate with an air excess ratio of over 3. More than half of the air is available for the combustion process, while the remaining part is scavenged through the cylinder. Hence, the exhaust gas contains some 13-16% oxygen, and this has to be considered when calculating the concentration of various compounds in the gas. Some exhaust gas emission regulations refer to 15% oxygen; so, if the actual content is different, the result will have to be corrected accordingly.

Nitrogen makes up about 80% of the atmosphere. Given the above-mentioned air excess ratio, it is clear that nitrogen constitutes the major part of the exhaust gas. As nitrogen is practically inactive, only a small but, as will be seen later, an important part is involved in the chemical reactions in the engine.

Carbon Dioxide, Water Vapour. Basically, the complete combustion of hydrocarbons will produce carbon dioxide and water vapour, and the relative amounts of these will be a function of the hydrocarbon composition. Carbon dioxide, although not toxic, has recently been given much attention because of the so-called ‘greenhouse effect’. The use of machinery with a high thermal efficiency and of fuels with a relatively low carbon content is the only viable means of reducing carbon dioxide emission.

Carbon Monoxide (CO) is a toxic gas. The formation of CO is, in principle, a function of the air excess ratio and the combustion temperature. The formation is strongly influenced by the uniformity of the air/fuel mixture in the combustion chamber, and we expect this to be the decisive factor in our engines.

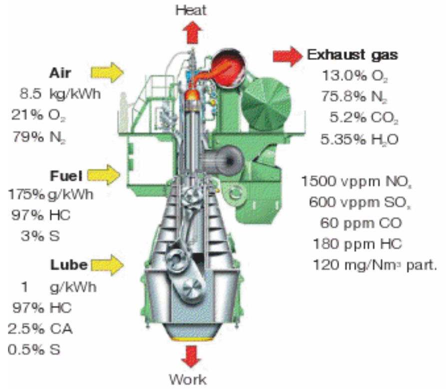


Figure 1. Typical emissions from an MC type low-speed diesel engine

Smoke. A traditional measure of the combustion quality, and a traditional way of qualifying the 'emission', is to look at, or to measure, the smoke intensity. The exhaust gas plume, when it leaves the top of the stack, may be visible for various reasons, e.g. its content of particulate matter and nitrogen dioxide, NO2 (a yellow/brown gas), or of condensing water vapour. Although it may be argued that these components are either subject to separate legislation (NOx, particulate matter) or not harmful (water), it is a fact that smoke and/or opacity limits are enforced in certain countries, e.g. in the USA.

Particulate Emissions in the exhaust gas may originate from a number of sources:

- agglomeration of very small particles of partly burned fuel,
- partly burned lube oil,
- ash content of fuel oil and cylinder lube oil,
- sulphates and water.

In general, the particles are small, and it can be expected that over 90% will be less than 1 μm when heavy fuel oil is used, excluding flakes of deposits, peeling-off from the combustion chamber or exhaust system walls, which in general are much larger.

Hydrocarbons. During the combustion process, a very small part of the hydrocarbons will leave the process unburned, and others will be formed. These are referred to as unburned hydrocarbons, and they are normally stated in terms of equivalent CH4 content. The content of hydrocarbons in the exhaust gas from large diesel engines depends on the type of fuel and the engine adjustment and design.

Oxides of Sulphur. Because of the organic origin of fuel oils, various amounts of sulphur are present in the oil injected into the combustion chamber. During combustion, the fuel sulphur is oxidized into different oxides of sulphur (SOx), mainly SO2 and SO3, typically in a ratio of 15:1. The emission of SOx from the engine is therefore a function of the sulphur content in the fuel oil. SOx can only be controlled by either removing the sulphur from the fuel or completely or partially removing the SOx from the exhaust gas by cleaning.

Nitrogen Oxides (NOx) are formed during the combustion process within the burning fuel sprays. NOx is controlled by local conditions in the spray with temperature and oxygen concentration as the dominant parameters. At the temperature in the burning fuel spray, nitrogen is no longer inactive, and oxygen and nitrogen will inevitably react to form oxides of nitrogen. A rule-of thumb says that a change of $100^{o}C$ in combustion temperatures may change the NOx amount by a factor of 3. The immediate reaction is the formation of NO. Later in the process, during expansion and in the exhaust system, part of the NO will convert to form NO2 and N2O, typically 5% and 1%, respectively, of the original NO amount.

Basically, two-stroke low-speed diesel engines are optimized for high efficiency, i.e. low fuel consumption, and for adequate combustion chamber temperature control, providing high reliability and long time between overhauls. Hence, the NOx emission from uncontrolled engines is, as already shown in Figs. 1 and 2, fairly high.

Oxides of nitrogen in the atmosphere contribute to the 'Smog formation' which is a considerable problem in many cities. The conversion of NO to NO2 will continue in the atmosphere but, since NO2 – unlike NO – is easily soluble in water, NO2 will be washed out by rain and will eventually increase the acidity of the soil. Accordingly, the effect of NOx is the same as that of sulphur but, unlike NOx, SOx can be reduced by limiting the sulphur content of fuels.

What is happening now, with the increased emission of NOx to the atmosphere from combustion, is disturbing a very delicate natural balance. Therefore, NOx control is advocated by environmentalists and legislators and, in fact, NOx control is the number one emission control issue. As mentioned earlier, NOx control represents a challenge for engine designers, and there are a number of ways of reducing the NOx (as will be discussed in the chapter on NOx reduction methods). However, all methods cause a certain loss in engine efficiency.

2. NOx Reduction Methods

NOx in the exhaust gas can be reduced with primary and/or secondary reduction methods. Primary methods are methods that affect the engine combustion process directly. The actual degree of reduction depends on engine type and reduction method, but varies from 10% to more than 50%.

The secondary methods are means of reducing the emission level without changing the engine performance from its fuel optimized setting, using equipment that does not form part of the engine itself. The most interesting secondary method so far is the SCR (Selective Catalytic Reduction) method of removing NOx. This method makes it possible to reduce the NOx level by more than 95% by adding ammonia or urea to the exhaust gas before it enters a catalytic converter.

Polluants of MAN B&W two-stroke diesel engines are NO_x (Nitrogen Oxides), SO_x (Sulphur Oxides), CO (Carbon Monoxide), HC (Hydrocarbons) and particulate emissions. NO_x is function of peak combustion temperatures and oxygen concentration and it can be reduced by primary and secondary methods. SO_x are function of fuel oil sulphur content and the most effective means is to lower the sulphur content in the fuel. CO is depending of the air excess ratio and combustion temperature and air/fuel mixture. Basically is very low for two-stroke engines. Hydrocarbons depends on fuel and lube oil types. During the combustion process a very small part of fuel and lube oil is left unburned. Particulate emissions are originate from partly burned fuel, ash content in fuel/cylinder lube oil, partly burned lube oil/dosage and deposits peeling off in the combustion chamber/exhaust gas system.

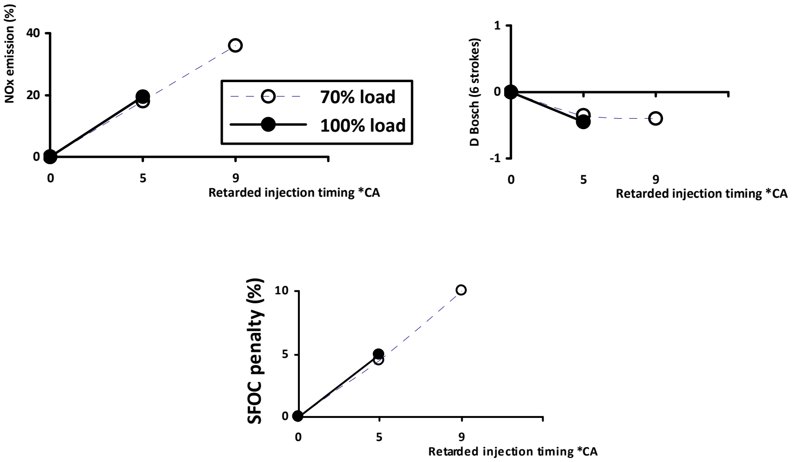


Figure 2. Effect of injection timing on SFOC, Bosch Smoke Number and NOx

Since our engines use a high air excess ratio, automotive types of catalysts cannot be used. Furthermore, the heavy metals and the sulphur content in heavy fuel oil would cause automotive catalysts to deteriorate after a short period of operation. In the following, the various primary reduction methods available will be discussed together with the SCR method.

Firing pressure influence. Reducing the firing pressure via injection retardation will lower the peak temperature and thus reduce NOx, but it also inevitably leads to higher fuel consumption. The typical behavior of the three parameters (SFOC, Bosch Smoke Number and NOx) is shown in Figure 2 as a function of injection timing. It goes without saying that this is not a particularly attractive method, as fuel consumption is important.

Air quality control. The partial pressure of the reagents oxygen and nitrogen can only be influenced by changing the specific amount of air entering the engine, or by changing the ratio between oxygen and nitrogen. The ratio can be changed by exhaust gas recirculation (EGR). If 15 per cent of the exhaust gas is recirculated, the resulting oxygen concentration in the intake air will be reduced from about 21 per cent (atmospheric) to around 18 per cent, and the impact on NOx formation will be significant.

Fuel nozzle adaptation/fuel injection. Fuel nozzle adaptation is a natural part of any prototype test, along with the verification of performance at different layouts. During such tests, it has been verified that different fuel nozzle types have a significant impact on NOx, and that the intensity of the fuel injection also has an influence. Table 1 shows the influence of different fuel nozzles on NOx formation as well as the influence on fuel consumption and other pollutants.

Table 1. *Effect of fuel valve and fuel nozzle design for a 12K90MC at 90% load*

Test results	NO$_x$	CO	Smoke	Δ SFOC
Units	ppm/15% O$_2$	ppm/15% O$_2$	BSN$_6$	g/bhph
Standard valve/nozzle	1594	109	0.35	0.0
6-hole fuel nozzle	1494	108	0.23	+ 0.4
Slide tzpe fuel valve	1232	87	0.18	+ 1.8
BSN$_6$ is the direct reading of the Bosch Smoke Number after six pump strokes				

Water emulsification. A standard engine design permits the addition of some 20 per cent of water at full load, thanks to the volumetric capacity of the fuel injection pumps, but this does not represent a limit from the combustion point of view. Water amounts of up to 50/50 fuel/water have been tested. In commercial application (see below) these water amounts will call for engine modification during construction. Figure 3 shows the impact on NOx and fuel consumption. The influence of water emulsification varies with the engine type, but generally one per cent of water reduces NOx by one per cent.

The emulsification is done before the circulating loop of the fuel oil system, i.e. at a point in the fuel flow to the engine from which there is no return flow. It is thus the fuel flow that controls the water flow, but the water addition could also be controlled by actually measuring the NOx in the exhaust. This would be the case if continuous monitoring of NOx was required.

For vessels using emulsified fuel, a specially designed safety system is built into the external fuel oil system so that electrical black out on board will not influence the fuel/water emulsification stability, and the engine can be started up without changing to fuel without water.

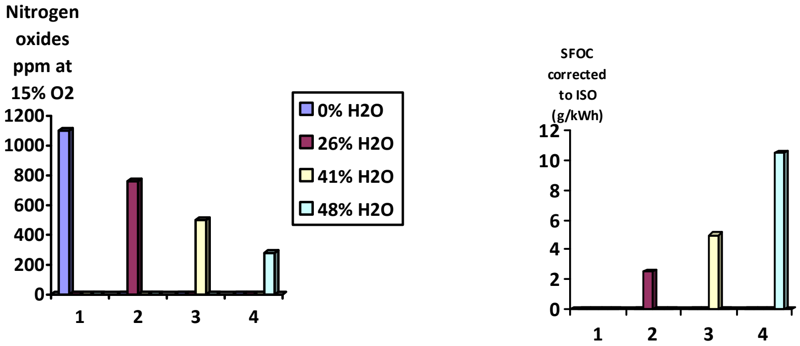


Figure 3. Effect of water emulsification on NOx emission and SFOC

Water injection or humidification. Water can also be added to the combustion chamber through separate nozzles or by means of stratified injection of water and fuel from the same fuel nozzle. The results are similar to the results of water emulsification, but water emulsification is simpler to apply and minimizes water consumption.

Another way to introduce water into the combustion zone is by humidifying the scavenge air. However, knowing that too much water in the scavenge air may be harmful to the cylinder condition, and that we therefore use water mist catchers as standard after the scavenge air cooler, this method is not appealing.

Cumulative effect. On a number of occasions we have had the opportunity to test the effect of most of the abovementioned methods, individually and in combination, on production engines. Obviously, the results of the different methods are not fully cumulative, but with the simple technology described so far, we have demonstrated NOx reductions of up to 80 per cent of the uncontrolled figure, a reduction level hitherto only thought possible with catalysts. However, it must be borne in mind that catalysts are proven technology, whereas the primary methods, apart from water emulsification and special low-NOx fuel nozzles, have little commercial background.

Selective Catalytic Reduction (SCR) is one of the most cost-effective and fuel-efficient diesel engine emissions control technologies available. For passenger cars and light duty trucks, the ability to meet strict emissions and fuel efficiency guidelines affordably without compromising driving power and performance is attractive. In the commercial trucking industry, including heavy and medium duty trucks, the ability to reduce emissions to near-zero levels while also delivering a 3-5% diesel fuel savings distinguishes SCR as one of the only emissions control technologies that is as good for business as it is for the environment.

SCR technology is designed to permit nitrogen oxide (NOx) reduction reactions to take place in an oxidizing atmosphere. It is called "selective" because it reduces levels of NOx using ammonia as a reductant within a catalyst system. The reducing agent reacts with NOx to convert the pollutants into nitrogen, water and tiny amounts of carbon dioxide (CO2) - natural elements common to the air we breathe everyday. The reductant source is usually automotive-grade urea, otherwise known as Diesel Exhaust Fluid, which can be rapidly hydrolyzed to produce the oxidizing ammonia in the exhaust stream. SCR technology alone can achieve NOx reductions in excess of 90%.

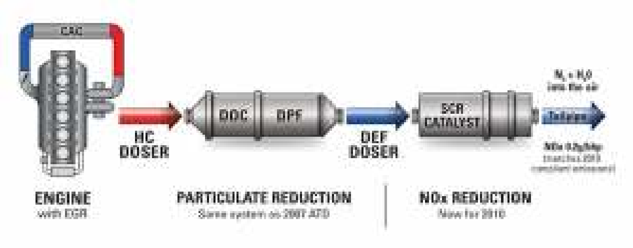


Figure 4. SCR techology

By this method, the exhaust gas is mixed with ammonia, NH3 before passing through a layer of a special catalyst at a temperature between 300 and 4000^{0}C, whereby NOx is reduced to N2 and H2O.

The assumed reactions are the following:

$$4NO + 4NH3 + O2 \rightarrow 4N2 + 6H2O \tag{1}$$

$$6NO2 + 8NH3 \rightarrow 7N2 + 12H2O \tag{2}$$

As can be seen, oxygen must be present for the process. If the temperature is too high, NH3 will burn rather than react with the NO/NO2. At too low a temperature, the reaction rate would be too low, and condensation of ammonium sulphates would destroy the catalyst.

The amount of NH3 injected into the exhaust gas duct is controlled by a process computer dosing the NH3 in proportion to the NOx produced by the engine as a function of engine load. The relationship between the NOx produced and the engine load is measured during test runs on the engine tested. The relationship obtained is programmed into the process computer and used for the feed-forward control of the NH3 dosage. The ammonia dosage is subsequently adjusted for bias by a feedback system on the basis of the measured NOx outlet signal.

The reason for choosing this method, rather than controlling the ammonia on the basis of the measured NOx outlet signal only, is that, with the latter method, the reactor would be too slow in responding to changes in the NH3 dosage, and this would result in excessive variations in NOx and/or ammonia outlet concentration.

The NOx measuring instrument is an integral part of the NH3 dosage control equipment. All instruments are mounted on a separate panel located in the engine control room. An oxygen analyzer and an NH3 alarm device are also incorporated, together with a strip chart recorder, which provides continuous monitoring of system performance.

The degree of NOx removal depends on the amount of ammonia added (expressed by the NH3/NOx ratio). At high NH3/NOx ratios, a high degree of NOx removal can be obtained but, at the same time, the amount of unused ammonia (called the NH3 slip) in the cleaned flue gas will increase. It is desirable that the concentration of unused ammonia in the cleaned gas is as low as possible. This is because when the flue gas in the downstream boiler or heat exchanger cools, the ammonia may react with SO3 in the exhaust gas and the heating surface may be fouled by ammonium sulphates.

The ammonia feed can be either liquid, water-free ammonia under pressure, or aqueous ammonia solution at atmospheric pressure, or it can be urea which can be carried as a dry product and dissolved in water before use.

The NH3 is a combustible gas, and is therefore supplied through a double walled pipe system with appropriate venting and an NH3 leak detector installed in the annulus space. The NH3 is diluted with pressurized air from the scavenge air receiver and subsequently mixed in a static mixer. The mixture of NH3 and air is injected into the exhaust pipe from the receiver and mixed with the exhaust gas in a second static mixer. In order to ensure the efficient operation of the SCR process, and to minimize the NH3 slip from the SCR reactor, it is important to obtain a homogeneous mixture of the NH3 and the flue gas.

The SCR reactor contains several layers of catalyst. The catalyst volume and, consequently, the size of the reactor depends on the activity of the catalyst, the desired degree of NOx reduction, the NOx concentration, the flue gas pressure and the acceptable NH3 slip.

The amount of catalyst can be expressed by the term space velocity (abbreviated NHSV), which is defined as the number of cubic meters of exhaust gas per hour which are treated per cubic meter of catalyst.

Figure 5 shows an example of how the NOx reduction and the NH3 slip vary with the NH3/NOx ratio for two different catalyst volumes (NHSV). As can be seen, both the NOx reduction and the NH3 slip increase with an increasing NH3/NOx ratio. It can also be seen that the same NOx reduction (for example 80%) can be obtained by using only half the catalyst volume (NHSV = 10,000 Nm3/m3h instead of 5,000 Nm3/m3h) just by increasing the NH3/NOx ratio a few per cent. At the same time, however, the ammonia slip increases considerably. Therefore, the maximum acceptable ammonia slip has a strong influence on the amount of catalyst required. Normally, the SCR units are designed for a steady state ammonia slip of 5-10 ppm during the lifetime of the catalyst.

Figure 5 also illustrates that, if a higher degree of NOx reduction is desired, it is necessary to increase the catalyst volume to keep the ammonia slip low at the same time. At a higher degree of NOx conversion, the need for accurate control of the ammonia addition (NH3/NOx ratio) increases. If the NH3/NOx ratio exceeds 1.0, the ammonia slip will increase considerably because of the amount of unused ammonia.

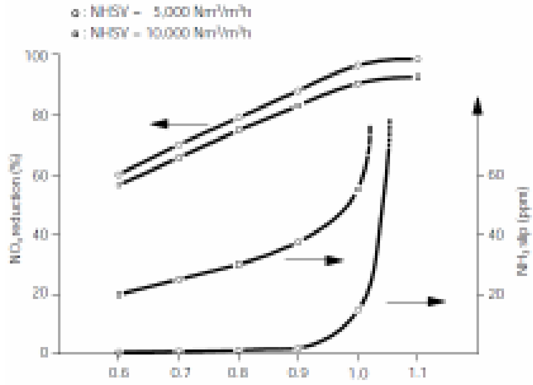
The catalyst has a monolithic structure, which means that it consists of blocks of catalyst with a large number of parallel channels, the walls of which are catalytically active. The channel diameter has an influence on the pressure drop across the catalyst as well as on the risk of dust depositing on the catalyst.

The channel diameter is optimized after a study of the dust content, the composition of the exhaust gas, and the permissible pressure drop across the SCR reactor.

In collaboration with the Danish chemical engineering company of Haldor Topsoe A/S (HTAS), MAN B&W has developed this method – well known from industrial applications – for use on diesel engines (Ref. [2]). A pilot test was carried out over a period of 4000 hours on a 12L55GSCA diesel power plant in the Faroe Islands. A small part of the exhaust gas was diverted from the exhaust gas receiver, while the engine was running on heavy fuel oil of 380 cSt /50^0C with 2.5% sulphur and 0.04% ash content.

During the first part of the test run there were problems with dust accumulation, which caused the pressure drop across the catalyst to increase. After about 2000 hours of operation, the problem was solved by the installation of a better gas distribution system upstream from the catalyst. Subsequently, the pressure drop and the activity remained constant during the last 2000 hours of the test. The catalyst was also mechanically unaffected by normal vibrations of the engine. Consequently, the influence of the SCR on the operation of the turbocharger can be predicted and corrected for in advance, so the influence on engine reliability will be negligible. On this basis, the SCR technology was cleared for commercial application.

In addition to the NOx reduction, some of the soot and hydrocarbons in the exhaust are also removed by oxidation in the SCR reactor.



Source: HTAS

Figure 5. Calculated NH3 slip and NOx reduction as function of NH3/NOx ratio for two given space velociti*es*

3. Proposed Rules and Ways of Meeting Them. IMO proposal

Since the discussion of the present IMO speed-dependent NOx- limit curve, see Figure 6, started, engine builders have advocated that rules and rule administration should be simple and pragmatic. Although all the details have not yet been settled, the work for simplicity and pragmatism as well as established industry-business patterns are respected in the IMO rule proposal.

In order to arrive at the IMO-NOx figures for a given engine, the NOx emission must be measured at different loads following the guidelines given in ISO 8178 (Ref. [1]). A typical NOx curve is shown in Figure 7 with the IMO-NOx value calculated to 19.5 g/kWh, i.e. relatively close to the IMO limit of 17 g/kWh for an engine with an MCR speed of 91 rpm.

The fine-tuning of the engine performance for optimum fuel consumption in a shop test, particularly for the first unit of an engine type that comes into service, will have an impact on the shape and level of the load dependent NOx curve. This means that the NOx value predicted or expected for any given engine can only be regarded as a guide. The NOx value must be established by tested measurements.

Therefore, an engine which, in the project phase, is offered with both a guaranteed fuel rate and a NOx limitation will carry both a fuel penalty and a higher tolerance because, as mentioned before, fuel consumption and NOx are not independent parameters. Instead of the 3% fuel tolerance, a 5% tolerance will be observed when the proposed IMO rules are adopted. With regard to meeting the IMO proposal for ships built today, we will apply low-NOx fuel injection nozzles. It is expected that IMO, five years after the introduction of the speed related curve, will present further limitation of the NOx, and this could call for water emulsification. The actual method to be used at that time will be selected after the level of uncontrolled NOx for the engine in question has been established on tested.

Catalysts will be used only where very strict individual rules are enforced, i.e. for certain stationary plants and maybe for special areas at sea.

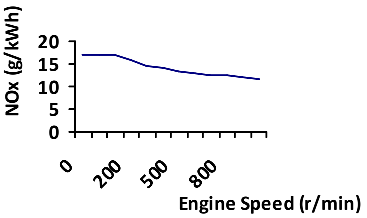


Figure 6. Target emission levels of IMO

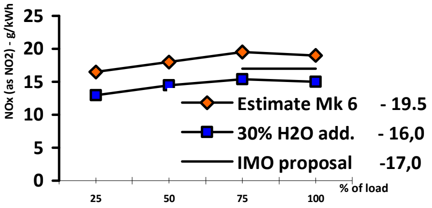


Figure 7. Typical load-dependent NOx curve, 6S70MC

$$\begin{aligned} NO_x\ (g/kWh) &= 17 \text{ x} && n<130 \\ &= 45 \text{ x } n^{0,2} && 130<n<2.000 \\ &= 9,8 \text{ x } n && n>2.000 \end{aligned}$$

where n is engine speed in r/min.

4. Conclusion

The de-NOx system aims at a reduction of the NOx concentration in the exhaust gas to 130 ppm. The NOx control takes place both on the ocean and in bay and river waters, subject to relatively large local variation. The entire voyage in NOx controlled waters will thus comprise both periods with de-NOx on and de-NOx off in order to ensure turbocharger performance and appropriate engine load response. The NOx concentration and the actual load profile are therefore integrated, and the result which is of real interest – the NOx emission in lb/trip – is calculated.

The SCR system has thus demonstrated satisfactory performance with regard to NOx removal. However, fine tuning may reduce NOx even further.

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