

Methodology to define NO_x emissions by ships in port

Germán de Melo Rodríguez

Polytechnic University of Catalonia

Spain

Ismael Cobos Delgado

Government of Spain

Abstract

This paper tries to show the methodology used to establish the NO_x emissions from the ships. In addition, the operation conditions of the ships in sailing periods, during manoeuvres and in port calls must be established.

The methodology we have considered in the paper is based in estimating the NO_x emissions by means of the specific consumption applying the named emission factors per fuel mass unit consumption. The fuel consumption depends on the ship's operations, the machinery used in them and also the load of that machinery.

To get the expected results we need to define by means of models the power of propulsion and electric generation machinery per ship type. Afterwards, it is necessary to know the curves of power/specific consumption in medium and slow speed engines for the load ranges required in the operation conditions to be analysed.

The emission factors in medium and slow speed engines for different operation loads of machinery also must be found.

With all the mentioned data, the NO_x emissions can be calculated per ship type. After calculations per ship type and knowing traffic or operations of ships in the cases to be considered, the total emissions in each case can be evaluated.

The possible cases to be analysed could be areas especially sensitive because of the traffic concentration; areas considered as control areas by the Annex VI of MARPOL and ports.

1 Objective

The purpose of the present paper is to define the methodology to determine the NO_x emissions from ships during their calls in port.

It also aims to establish the operation conditions during the navigation in port, manoeuvres and berth operations.

2 NO_x generation process in heat engines

The nitrogen oxides, usually represented by NO_x, are one of the pollutants generated in the combustion process whose emission is more severely limited every day by legislation.

In the maritime industry the NO_x emissions from the ships are limited by the MARPOL Annex VI.

NO_x is a set of different nitrogen oxides: NO, NO₂, N₂O, NO₃, N₂O₃. The quantity of oxides generated decreases from the left to the right of the list; NO represents the biggest concentration and only NO, NO₂ and N₂O are considered as relevant constituents of NO_x.

There are three generation processes of NO_x: Thermic NO, NO of the fuel oil, and prompt NO.

The thermic NO is formed from a reaction of oxygen and nitrogen in the air. This reaction needs a big quantity of activation energy, then the generation of NO_x increases exponentially when the temperature increases. To reduce the generation of thermic NO, the temperatures must be reduced during the combustion process and when it is possible the concentration of oxygen must also be reduced in part of the combustion process.

The NO of the fuel oil is formed from a reaction of the oxygen of the air and the nitrogen of the fuel oil. This can be generated at lower temperature values than the NO thermic. It is important when the fuel oil has a high content of nitrogen.

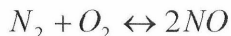
The prompt NO is a process of NO generation related with radicals such as CH and C₂. It is still not well known, but it implies a quicker NO generation than the other processes. It is not very important in the case of diffusion flames of high turbulence as in the diesel engines.

Of them, the NO thermic is the most important because of its contribution to the NO_x generation.

The reactions of generation are as follows:

REACTION	SPEED CONSTANT
$O + N_2 \rightarrow NO + N$	$K_1 = 1,82 \cdot 10^8 \exp(-38370/T)$
$N + NO \rightarrow N_2 + O$	$K_{-1} = 3,93 \cdot 10^7 \exp(-450/T)$
$N + O_2 \rightarrow NO + O$	$K_2 = 3,80 \cdot 10^4 \cdot T^{0,9085} \exp(-4837/T)$
$O + NO \rightarrow O_2 + N$	$K_{-2} = 3,80 \cdot 10^3 \cdot T \exp(-20820/T)$
$N + OH \rightarrow NO + H$	$K_3 = 5,034 \cdot 10^6 \cdot T^{0,297} \exp(-50/T)$
$H + NO \rightarrow OH + N$	$K_{-3} = 1,70 \cdot 10^8 \exp(-24560/T)$

All of them can be grouped in a global reaction:

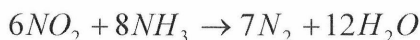


Since the NO_x generation mainly depends on the temperature, the immediate way to reduce it is through the reduction of the temperature during the combustion process. This implies the reduction of the effectiveness of the thermodynamic cycle and the increase of fuel oil consumption. This has been the origin of the “diesel dilemma:” if the NO_x generation is reduced, the fuel oil consumption is increased, and if the fuel oil consumption is to be reduced the NO_x generation suffers an important increase.

The methods to reduce the temperature during the combustion process in diesel engines include: delay of the combustion, add water in the combustion chamber which is going to be evaporated absorbing heat, re-circulate part of the exhaust gases by introducing them in the combustion chamber.

Reducing the air during part of the combustion process cannot be done in diesel engines because the fuel oil is diffused in the cylinder full of air, but it can be done in boiler burners in which the air is reduced in high temperature combustion areas, and it is added in lower temperature areas to complete the combustion process.

An alternative to avoid the NO_x generation is to eliminate them after their generation. This can be done in marine diesel engines by means of the technique SCR (selective catalytic reaction) which consists of injecting nitrogen or urea in the exhaust gases inside a catalyser where the next reactions take place:



Thus, the NO_x generation significantly depends on the fuel oil consumption, and this consumption depends on the ship’s operations, the machinery used, its operation regime, and the power installed on board.

3 Conditions affecting the fuel consumption in the different operative stages of the ship: Manoeuvring, berthed (hoteling and loading/unloading) and anchored

Operations of ships related with the fuel oil consumption:

- Propulsion for navigation and for manoeuvres in port.
- Electric supply for navigation and for the systems and equipment for manoeuvres in port, loading/unloading operations, conditions in the ship.

3.1 All ship types propulsion conditions during manoeuvres

Estimate of the propulsion power while sailing in port: To find it, we will consider the generally accepted mathematics model called the Admiralty Formula:

$$P = \frac{\Delta^{2/3} \cdot v^3}{C_A}$$

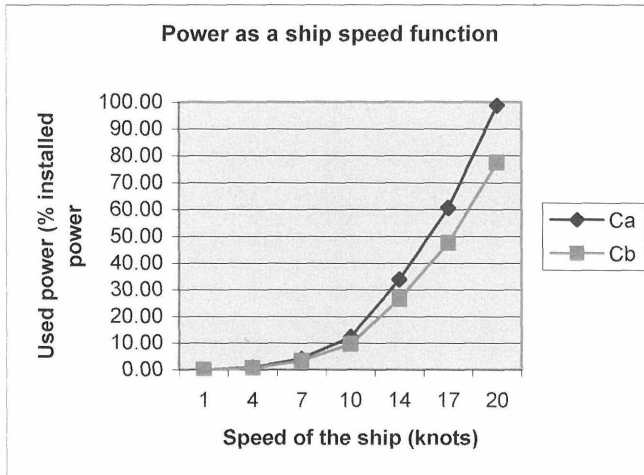
P = Power in IHP

Δ = Displacement of the ship in Long Tons (1 Long Ton= 1,016 t)

v = Speed of the ship in knots

C_A = Admiralty coefficient. Values between 264 – 336

As an example, it shows a containership whose displacement is 33640 t and the main engine power is 32315 IHP. The above mentioned Formula results in the graphic for the percentile of available power used as a function of the ship's speed. The graphic C_a corresponds to an Admiralty coefficient value 264 and C_b corresponds to 336.



Taking into account that the ship's speed in port is limited to 4 knots approx., we consider that speed to calculate the necessary power for propulsion during manoeuvres:

$$P = \frac{33640^{2/3} \cdot 4^3}{300} = 207 \text{ IHP}$$

It can be seen that the relationship of calculated power by using the Formula and the indicated power of the ship (32315 IHP) is $6,4 \cdot 10^{-3}$, so 0,6%. To include the transient period to get the 4 knots speed from the stopped state, the power relationship is increased to 2%.

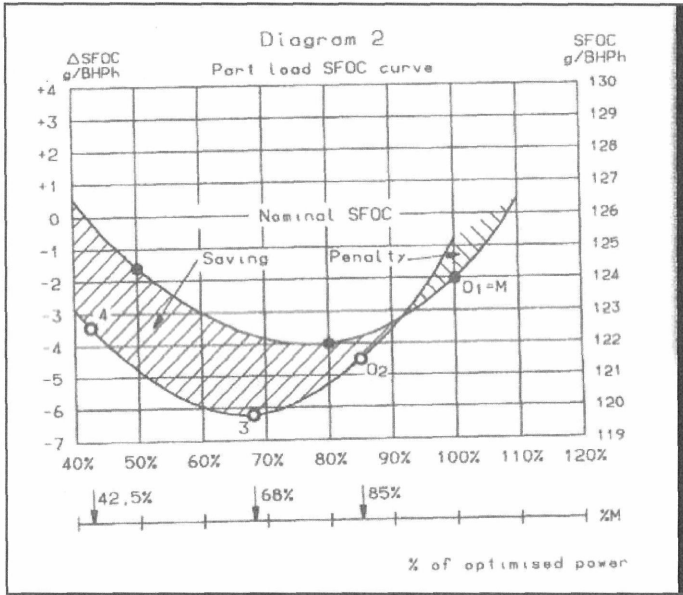
In addition, the applicability of that Formula at low speed and the exact value of the Admiralty coefficient has to be considered; for this reason to include these possible deviations, the relationship of power of the ship at manoeuvring load (4 knots) can be increased till 10%, for this case 3231,5 IHP.

Even though it has to be said that to get accurate results and because of the great influence of them in the NO_x emissions, a research job would be made.

With reference to the required time for manoeuvring from the entrance buoy to the berth, considering 4 knots speed and 2,5 h calculated as total time of the in/out manoeuvre in a model port as Barcelona, so that the time spent in this stage will be around 20% of the total time.

From the calculated power and knowing the specific F.O. consumption of the propulsion machinery (see diagram 1), the approximate F.O. consumption during the navigation in port can be found.

Diagram 1: Part load SFOC curve



Source: MAN B&W Diesel

Once the F.O. consumption has been obtained for the considered period and the corresponding emission factors have been applied (see table 1), the NO_x quantity produced in port navigation is obtained.

Observing the graphic of the SFOC, it is inferred that at low loads its value is very high: this must be held in account to calculate the emissions.

Table 1: NO_x Emission Factors

Table VII Lloyd's Register emission factors for steady state operation

	kg/t fuel		g/kWh	
	Medium speed engines	Slow speed engines	Medium speed engines	Slow speed engines
NO_x	59	84	13.8	18.7
CO	8	9	1.8	2.1
HC	2.7	2.5	0.6	0.5
CO_2	3250	3165	-	-
SO_2	21%	21%	-	-

S= Sulphur content of oil fuel (% by wt)

Source: Lloyd's Register of Shipping

The propulsion machinery emissions during the berthing operations will be negligible. To be considered, they could be calculated by increasing the navigation time in port at the corresponding load.

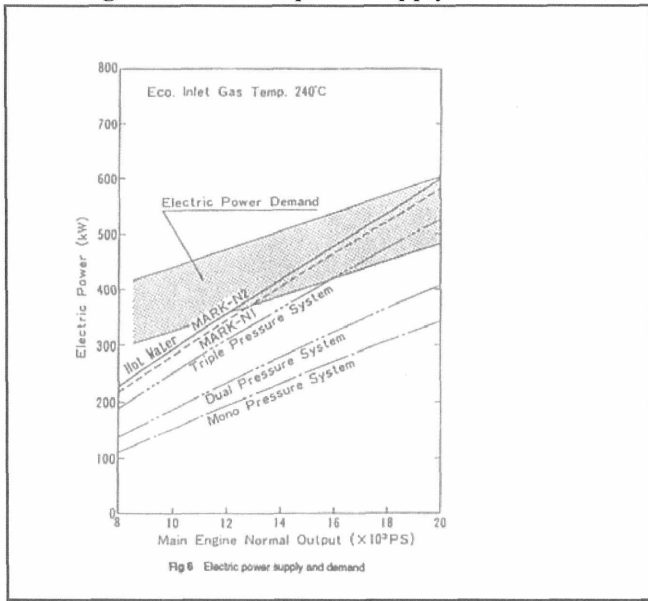
Finally, it is considered that the propulsion machinery is not running during the time the ship is berthed.

3.2 Auxiliary plant conditions during manoeuvres

Estimate of the auxiliary plant power while sailing in port and berthing operations: In general, for safety reasons during the ship's manoeuvres in port, two generators are running.

The power developed by the main generators will be considered that corresponding to navigation at sea (see diagram 2) increased between 20 and 30% due to the running of the necessary machinery required in the manoeuvres (steering gear, auxiliary blowers, bow thruster, deck machinery,...)

Diagram 2: Electric power supply and demand



Source: A. Fukugaki

Estimate of the auxiliary plant power while the ship is berthed: The auxiliary plant includes the electric power generators and the auxiliary boilers.

To establish the power, two different conditions have to be distinguished:

- a) When the cargo operations require the auxiliary machinery to be manned or maintained in condition.
- b) Hoteling condition.

Depending on the ship type one of the defined conditions will be analysed (see table 2).

Table 2
Average power in port operations

STEAM TURBINES PROPULSION SHIPS (% of the plant power)		
Type of ship	% of the total power unloading	% of the total power in Hotel condition
General Cargo	15	10
Bulk Carriers	10	10
Oil Tankers of less than 125000 DWT	30	15

ENGINE PROPULSION SHIPS (% of the power of the generators / boilers)				
Tipo de buque	Loading/Unloading		Hotel	
	Diesel Generators	Boilers	Diesel Generators	Boilers
General Cargo	65	50	30	50
Bulk Carriers	30	50	30	50
Oil Tankers of less than 125000 DWT	65	85	30	85

Source: Allen G. Hansen et al.

In most of the engine propulsion merchant ships consuming F.O., a boiler is installed to heat that F.O. and for other auxiliary services. This boiler is usually running in port.

The LNG ships are mainly powered by steam turbines which take advantage of the cargo boil-off to be consumed in the boilers.

There are some cruise ships powered by steam plants.

Table 2 contains the supplied power with reference to the installed power in two conditions. One of them is during the loading and unloading operations by using the ship's means and the other one while the ship is in hotel condition,

which corresponds to the electric power supplied only for the accommodation services, galley and safety elements.

In the steam propulsion table, it can be observed that depending on the ship's type (for example oil tankers of less than 125000 DWT) as compared to an LNG, when they are unloading the power is 30% of the total power of the plant.

In the engine propulsion table it can be observed that depending on the ship's type (for example bulk carriers) during the loading/unloading operations, there is an energy consumption of 30% of the diesel generators' power and of 50% of boiler's power.

Because of the special operative conditions of cruise ships and reefers, the complexity of the propulsion and auxiliary machinery configuration and the high electric power required to maintain the ship in normal conditions (operation and accommodation) the ratios of auxiliary plant referred to the propulsion plant are higher than in other types of ships, so that they require particular research to get emission values in port.

4 Conclusion

- The NO_x marine pollution is produced by the propulsion machinery and auxiliary machinery required for the electric power supply.
- The emissions can be quantified from the F.O. consumption by using the emission factors.
- The F.O. consumption for propulsion in port is calculated by means of the required power, obtained from the Admiralty Formula. It can be estimated as 10% of the installed power.
- The auxiliary machinery power depends on the developed operation and the ship's type. For conventional ships it can be estimated according to the data indicated in the table 2. For cruise ships and reefers it is necessary to research specifically both types of ships.

To determine the used power in the manoeuvring period of time, the research must be very accurate because of the disagreement found in different studies and its importance in the final results.

We conclude by indicating that during the navigation in port, the rating of the propulsion machinery is the same in all ship's types.

References

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