

The estimation of the pollutant emissions on-board vessels by means of numerical methods

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Abstract. Protection of the environment, especially within the most recent years, has become a constant problem considered by the states and the governments of the world, which are more and more concerned about the serious problems caused by the continuous deterioration of the environment. The long term effects of pollution on the environment generated by the lack of penalty regulations, have directed the attention of statesmen upon the necessity of the elaboration of normative acts meant to be effective in the continuous fight with it. Maritime transportation generates approximately 4% of the total of the CO₂ emissions produced by human activities.

This paper is intended to present two methods of estimation of the gases emissions on-board a vessel, methods that are very useful for the crews which are exploiting them. For the determination and the validation of these methods we are going to use the determinations from the tank ship. This ship has as a main propulsion engine Wärtsilä DU Sulzer RT Flex 50 – 6 cylinders that develops a maximal power of 9720 kW and has a permanent monitoring system of the pollutant emissions. The methods we develop here are using the values of the polluting elements from the exhaust gases that are determined at the exit of the vessel from the ship yard, in the framework of the acceptance tests. These values have been introduced within the framework of a matrix in the MATHCAD program. This matrix represents the starting point of the two mentioned methods: the analytical method and the graphical method. During the study we are going to evaluate the development and validation of an analytical tool to be used to determine the standard of emissions aimed at thermal machines on ships.

One of the main objectives of this article represents an objective assessment of the expediency of using non-fuels for internal combustion engines in vessels.

1. Introduction

The determinations and the calculations within this paper are based on the functional parameters of the installations on board the M/T Aristidis, 37 000 DWT, belonging to the company Capital Shipping Management with the headquarters in Pireu – Greece. This approach is based on the fact that in this study the experimental validations will be realized with the help of determinations realized on board the same ship.

The ship's propulsion installation is a two-stroke engine – axial line – fixed pitch propeller and a Wärtsilä – DU Sulzer RT flex 50 engine.



Table 1. The main characteristics of the ship

M/T Aristidis	
Built	2006, The Naval Hyundai Mipo ship-yard
Class	ABS +A1(E), Oil Carrier ESP, Chemical Carrier ESP, Ship type 2 in association with a list of defined cargoes including Caustic Soda, SH, SHCM, +AMS, +ACCU, V ECL, FL(25), ICE Strengthening 1A
Flag	Marshall Islands
Port of registry	Majuro
Call Sign	V7JD7
Owner	Atlantas Shipping CO., Majuro, Marshall Islands
Manager	Capital Ship Management Corp / 3, Iassonos Street Piraeus185-37, Grecia

**Figure 1.** The ship used for determinations of the functional parameters**Table 2.** Ship particularities

Ship type	Ice Class IA Product / Chemical IMO II / III Tanker
IMO Number	9327413
Displacement (Full Summer)	36 680 DWT
Draught (Full Summer)	11.3 m
Gross register tonnage	23 270 t
Net register tonnage	9 925 t
LOA	184.22 m
Beam	27.4 m
Maximum draught	17.2 m
KTM	45.51 m
Cargo loading facilities	
Cargo tanks	12
Slop tanks	2
The volume of the tanks (98% with the exception of the slop tanks)	40 754 m ³
The volume of the slop tanks (98%)	1034 m ³
The tanks heating installation	Heat exchangers of the SUS type of 316 L

Cargo pumps	FRAMO, submerged, hydraulic action (10 – 500 m ³ /h; 2 – 300 m ³ /h; 2 – 150 m ³ /h)
Energetic installations	
Main engine	Wärtsilä DU Sulzer RT Flex 50 – 6 cylindres
Auxiliary engines	3 Diesel generators Hyundai Himsen H 21/32 (1 D.G. – 800 kW; 2 D.G. 960 kW); 1 Diesel damage generator MAN B&W; 2 Auxiliary engines for starting the cargo pumping system of Cummins KTA19-D(M) type;
Steam generator	Kangrim
Inert gas installation	Kangrim
Oil and fuel separator	Alpha Laval SU 843 and P 610
Desalting	Donghwa Entec 30 t/daily

Table 3. Main engine

No.	Name	Value	Measurement unit
1.	Cylinder number	6	-
2.	Strokes number	2	-
3.	The reaming of the cylinder	500	[mm]
4.	The race of the piston	2050	[mm]
5.	Maximal power	9720	[kW]
6.	Service power (85 % MCR)	8265	[kW]
7.	Maximal speed	124	[rpm]
8.	Service speed (85 % MCR)	117	[rpm]
9.	The average speed of the piston	8.5	[m/s]
10.	The effective average pressure	19.5	[bar]
11.	Length	7712	[mm]
12.	Width	3150	[mm]
13.	Height	8840	[mm]
14.	Weight (with water and fuel in the installations)	225	[t]
15.	The fuel specific effective consumption	166.7	[g/kW·h]
16.	The specifically effective oil consumption for the cylinders	1.97	[g/kW·h]
17.	The ignition order	1-6-2-4-3-5-1	-
18.	The maximal burning pressure	155	[bar]
19.	The compression report	18.01	-
20.	The engine's registration number	DU-3675	-

The ship has on board three generators produced by Hyundai, HIMSEN H21/32 type and a spare diesel generator, produced by MAN B&W.

The characteristics of the diesel generators H21/32 are presented in the following table (table 4).

Table 4. Diesel generator

No.	Name	Value	Measurement unit
1.	Cylinders number	6 (5)	-
2.	Strokes number	4	-
3.	The cylinder's reaming	210	[mm]
4.	The piston's race	320	[mm]

5.	Maximal power	960 (720)	[kW]
6.	Maximal speed	720	[rpm]
7.	The apparent power of the propeller generators	1125 (925)	[kVA]
8.	The power factor ($\cos \varphi$)	0.82	-
9.	The produced tension	440	[V]
10.	Frequency	60	[Hz]
11.	The average speed of the piston	7.7 (8.0)	[m/s]
12.	The effective average pressure	24.1	[bar]
13.	The ignition order	1-4-2-6-3-5-1 (1-2-4-5-3-1)	-
14.	The maximal burning pressure	175 (180)	[bar]
15.	The compression ratio	17	-
16.	The engine's registration number	BA1782-1, BA1782- 2, BA1781	-

2. Specifications concerning data determination (methods and materials)

All along the modelling process, we have considered as reference data the values measured when the ship comes out from the shipyard, within the acceptance tests, upon which we have determined, through a graphical method, the variations of the concentrations of the pollutants, with regard to the parameters of the main engine.

When determining the concentrations of the pollutant components, a simplifying hypothesis was used according to which each pollutant concentration varies with the modification of a single functional parameter of the engine, the other parameters remaining constant, and thus having no influence on the concentrations. The hypothesis doesn't correspond to the real case of dependence of the concentrations according to the engine's parameters, but after undertaking the calculation of the specific emissions one may notice which are the parameters that influence the values of the specific emissions.

With the concentrations resulted from the graphical method, the values of the specific emissions have been determined for the measured parameters on-board, finally evidencing those parameters that influence the emissions.

The values of the functional parameters, obtained during the sea trials, are found on-board the ship published in “*NO_x Technical File*”, for each engine aside. These results will be used to determine the variation graphs of the pollutant concentrations according to different parameters and then with these relations one is to determine the emissions for the actual case.

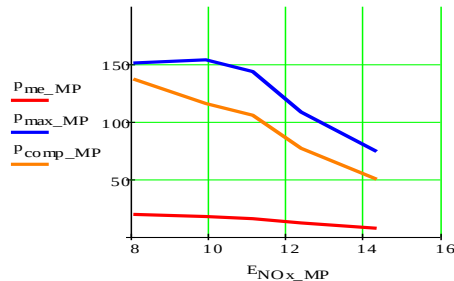
3. Interpretation of results (results and discussion)

3.1. The variation of the NO_x emissions at the average effective pressure modification, of the maximal burning pressure and of the compression pressure modification

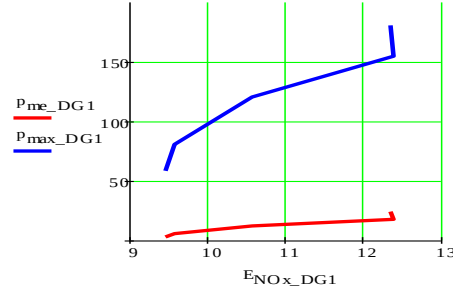
For the main engine we may notice that diminishing the maximal burning pressure or the compression pressure, results into an increase of the value of the emissions. This is opposed to the thermal mechanism of the NO_x forming, and it is achievable through the electronic control of the parameters of the burning and evacuation process. The engine functions generally at the burning pressures of 110 – 130 bar (corresponding to a speed of approximately 110 rpm), ensuring emission values below the limit of 17 g/kWh.

In the case of diesel generators the situation is different. The growth of the generator load leads to the growth in fuel consumption and that of the maximal pressure in the combustion chamber. At the same time, at high values of this pressure one reaches the limit of 2000 K, where the formation of NO_x becomes significant. But this temperature limit is reached only at combustion pressures that are higher than 150 bar, pressures that might be reached only in the case of values of very high generator loads. But this situation won't be accepted by the management system of the electrical power generator

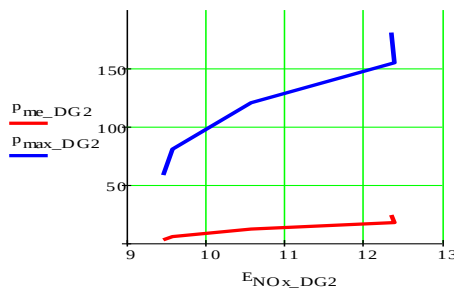
(Power Management System) that will cause the ignition of yet another generator for the load reduction.



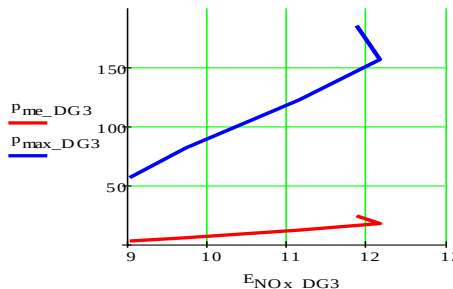
a) Variation of the NO_x [g/kWh] emissions, depending on the average effective pressure [bar], on the maximal pressure [bar] and on the compression pressure [bar] for MP



b) Variation of the NO_x [g/kWh] emissions, depending on the main effective average pressure [bar] and on the maximal pressure [bar] for DG no. 1



c) Variation of the NO_x [g/kWh] emissions, depending on the effective average pressure [bar] and on the maximal pressure [bar] for DG no. 2



d) Variation of the NO_x [g/kWh] emissions, depending on the effective average pressure [bar] and on the maximal pressure [bar] for DG no. 3

Figure 2. Determination of NO_x variation, according to the effective average pressure, the maximal pressure and the compression pressure

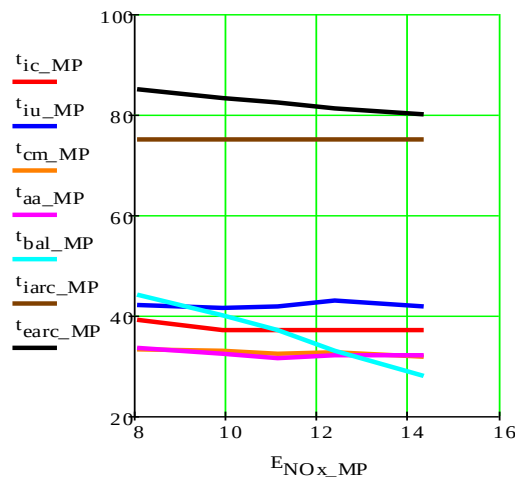
In the case of engines used for cargo pumps, the variation of the NO_x emissions has the same shape as in the previous cases. The moderation of the injection ensures an interval in which the NO_x emissions are reduced and don't surpass the limit of 9.8 g/kWh, for values of the effective average pressure comprised between 7 – 13 bar.

3.2. Variation of the NO_x emissions at different functional temperatures

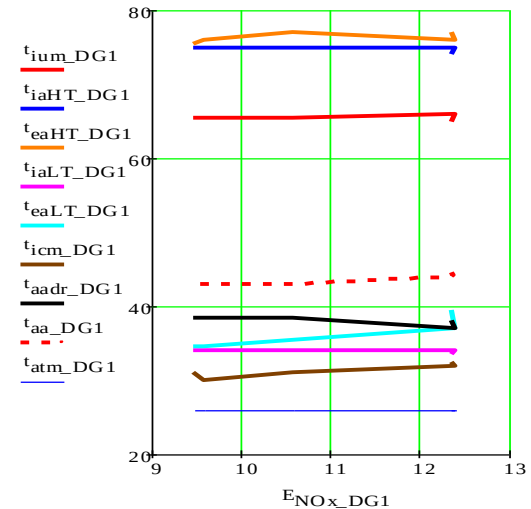
In these diagrams we have only taken into account the temperatures of the supply and scavenging air, of the lubrication oil, of the cooling water, of the fuel and the temperature in the compartment. The temperature of the exhaust gases will be considered separately.

But one may notice that the cooling of the scavenging air implies a growth of the emission values. This variation is not normal, being possible only when the parameters of the burning process are altered, as in the case of the main engine, where these parameters are controlled by a computer in order to diminish emissions. Normally, when cooling the supply air and introducing it in the cylinders, the value of the emissions should decrease, because the burning temperature might be a bit reduced. The same abnormal variation is also observed when reducing the temperature of the cooling water at the exit from the cylinders. This temperature should be higher as the load of the engine and the emissions increase. But the electronic control system of the engine, through the adjustment of the burning parameters, determines the apparition of these abnormal parameters variations.

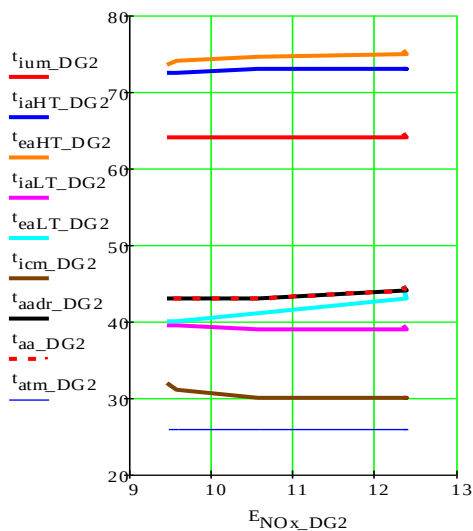
In the case of the diesel generators, all the parameters variations are small, but normal. They follow the law according to which the emissions increase at the growth of the temperatures of the supply air, of the cooling water, of the fuel and lubrication oil.



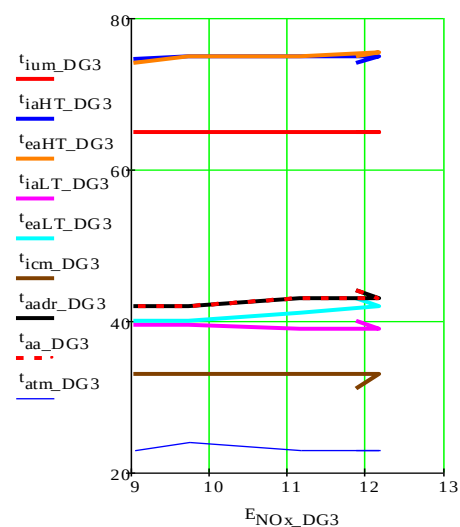
a) Variations of the NO_x [g/kWh] emissions, depending on the fuel entry temp. [°C], oil entry temp. [°C], temp. in the engine compartment [°C], supply air temp. [°C], scavenging air temp. [°C] and the entry and exit temp. of the cooling water from the cylinders [°C] for MP



b) Variations of the NO_x [g/kWh] emissions, depending on the entry temp. of oil in the engine [°C], the entry and exit temp. of water HT [°C], the entry and exit temp. of water LT [°C], fuel entry temp. in the engine [°C], the temp. of supply air before and after the cooler [°C] and the atmospheric temp. [°C] for DG no. 1



c) Variations of the NO_x [g/kWh] emissions depending on the entry temp. of oil in the engine [°C], the entry and exit temp. of water HT [°C], the entry and exit temp. of water LT [°C], the fuel entry temp. in the engine [°C], the supply air temp. before and after the cooler [°C] and the atmospheric temp. [°C] for DG no. 2



d) Variations of the NO_x [g/kWh] emissions, depending on the oil entry temp. in the engine [°C], the entry and exit temp. of water HT [°C], the entry and exit temp. of water LT [°C], the fuel entry temp. in the engine [°C], the supply air temp. before and after the cooler [°C] and the atmospheric temp. [°C] for DG no. 3

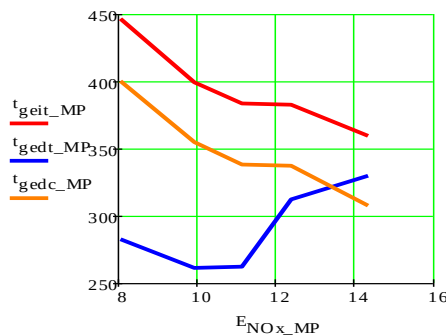
Figure 3. Determination of the NO_x variation depending on the functional temperatures

For the main engine, one may notice that the following temperatures influence in a very small margin the emissions: the entry temperature of the cooling water, the entry temperature of the lubrication oil, the entry temperature of the fuel, the compartment temperature and the temperature of the supply air.

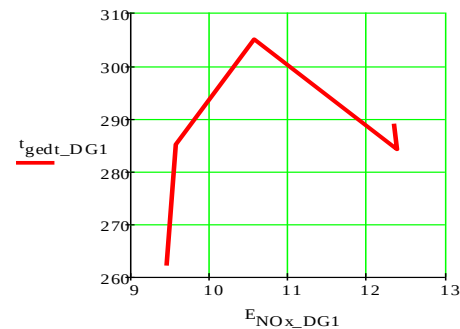
For the engines of the cargo pumps, one may notice the same shape of the variation curves, as in the latter paragraphs. This variation is caused by the action of the variable injection strokes on the combustion process. For any of the functioning temperatures of the engine, the values in the middle of the variation interval correspond to some reduced emissions; because that is the area in which VIT (variable injection strokes) act in order to reduce them.

3.3. Variation of the NO_x emissions depending on the modification of the exhaust gases temperature

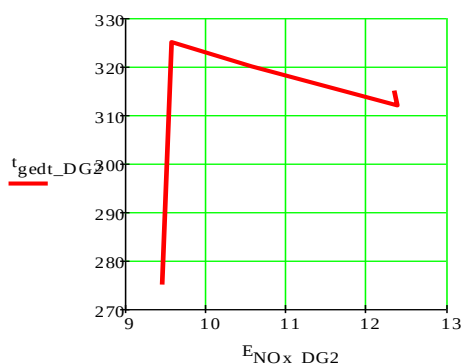
Studying the variation diagrams of the NO_x emissions depending on the temperatures of the exhaust gases, for the main engine, one may notice that when temperature of the exhaust gases drops at the exit from the cylinders and at the entry in the turbine, the emissions increase. This variation is not a normal one, because the value of the emissions should decrease, but it is possible due to the electronic control of combustion and of the exhaust in the case of the main engine. Concerning the temperature of the exhaust gases at the exit from the turbine, one may notice a return to the normal variation of the emissions, meaning that when the temperature increases, the emissions also increase.



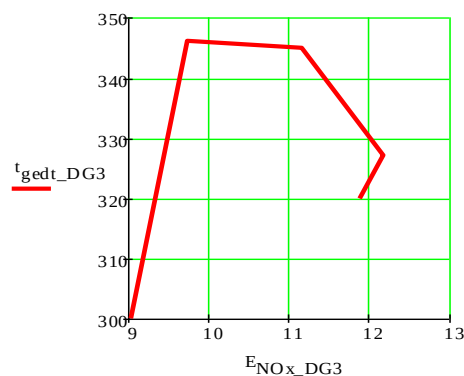
a) Variation of the NO_x [g/kWh] emissions depending on the temperature of the exhaust gases, before the turbine and after the cylinders [°C] for MP



b) Variation of the NO_x [g/kWh] emissions depending on the temperature of the exhaust gases [°C] for DG no. 1



c) Variation of the NO_x [g/kWh] emissions depending on the temperature of the exhaust gases [°C] for DG no. 2



d) Variation of the NO_x [g/kWh] emissions depending on the temperature of the exhaust gases [°C] for DG no. 3

Figure 4. Determination of the NO_x variation depending on the temperature of the exhaust gases

In the case of diesel generators, one may state, with regard to the shape of the variation that for all three generators, at a maximum load, the temperature of the exhaust gases tends to decrease. This decrease also corresponds to a light decrease of the emissions, even thinner in the DG 2 case and more intense in the DG 1 case. In the other variation areas, the value of the emissions increases at the same time with the decrease of the temperature of the exhaust gases.

For the engines of the cargo pumps, one notices the same shape of the variation between the two parameters, determined (the shape) by the action VIT in the middle of the temperature interval of the exhaust gases, area which corresponds to the diminished values of the emissions.

4. The analytical method of determining concentrations

First, one defines two column matrixes, in which one introduces the parameters resulted at the measurements in the shipyard, parameters that will be used for determining a mathematical relation.

The matrixes are:

$$T_{ev_MP1} := \begin{pmatrix} 359 \\ 382 \\ 383 \\ 399 \\ 446 \end{pmatrix} \quad C_{NOxR_MP1} := \begin{pmatrix} 1079 \\ 981 \\ 875 \\ 780 \\ 641 \end{pmatrix} \quad (1) \quad (2)$$

where:

T_{ev_MP1} – measured temperature of the exhaust gases from the main engine before the turbine;
 C_{NOxR_MP1} – the (real) measured concentration of NO_x corresponding to the main engine.

Then the transposed matrixes of the column matrixes are defined:

$$T_{ev_MP} := T_{ev_MP1}^T \quad (3)$$

$$C_{NOxR_MP} := C_{NOxR_MP1}^T \quad (4)$$

Then the difference between the maximum value and the minimal value of the NO_x concentration is determined, by using some functions that extract the data from the matrixes:

$$D_{NOxR_MP} := C_{NOxR_MP}^{\langle 0 \rangle} - C_{NOxR_MP}^{\langle 4 \rangle} \quad (5)$$

These data extraction functions will extract from the column matrixes the corresponding term to the defined exponent (in the latter case for the exponent 0 it shall extract the value of 1079, from row 1 of the matrix, and for exponent 4 it shall extract the value of 641, from the fifth row of the matrix, with the observation that exponent 1 corresponds to the value from the second row of the column matrix).

In the following phase the coefficients and the exponents that were used in the formula were defined, each one of them having a specific role in determining the optimal formula:

- z_{MP} – the graphical correlation exponent of the relation;
- x_{MP} – the coefficient that determines the order of the result (10^1 , 10^2 , 10^3 , etc.);
- y_{MP} – the correction exponent of the difference between the maximum and the minimum value of the concentration;

- m_{MP} – the correction coefficient of the minimum value of concentration.

The following stage is determining the formula through trials or by writing a determination program, until one obtains the optimal values of the four coefficients and exponents.

One defines the difference between the maximum and the minimum value of the NO_x concentration, which is calculated with the formula:

$$C_{NOxL_MP} := C_{NOxL_MP1}^T \quad (6)$$

$$D_{NOxL_MP} := C_{NOxL_MP}^{\langle 0 \rangle} - C_{NOxL_MP}^{\langle 4 \rangle} \quad (7)$$

The variation graph of the concentration calculated with the measured parameter will allow the appreciation of the resemblance between the real case of variation and the one determined by the resulted formula. One has to make the observation that the linear variations of the two parameters are necessary.

4.1. Example of determining the concentration of nitric oxides (NO_x) by using the analytical method

For determining of the NO_x concentration, we chose as a calculation parameter the temperature of the exhaust gases before the turbine (T_{ev}).

For the *main engine* we used the following data presented in table 5:

Table 5. The main engine data

Temp. of the exhaust gas before the turbine	T_{ev}	[°C]	359.0	382.0	383.0	399.0	446.0
The dry NO_x concentration	C_{NOxR}	[ppm]	1079.0	981.0	875.0	780.0	641.0

As a result of the calculation for determining the formula, the following errors resulted, table 6:

Table 6. The errors

E_{D_MP}	E_{M_MP}	E_{0_MP}	E_{1_MP}	E_{2_MP}	E_{3_MP}	ΔE_{MP}
1	0.006	0.006	8.884	1.333	0.012	1.883

Resulted values are acceptable, thus the determination relation is:

$$C_{NOxL_MP1} := \frac{x_{MP}^{y_{MP}}}{T_{ev_MP1}^{z_{MP}}} - \frac{1000m_{MP}}{y_{MP}^3} \quad [ppm] \quad (8)$$

In which the coefficients and exponents have the following values, table 7:

Table 7. The coefficients and exponents values

x_{MP}	y_{MP}	z_{MP}	m_{MP}
100	4.74885	2.5	22.39

The following figure presents the comparison graph of the real variation of the NO_x concentration with the calculated variation, for the main engine.

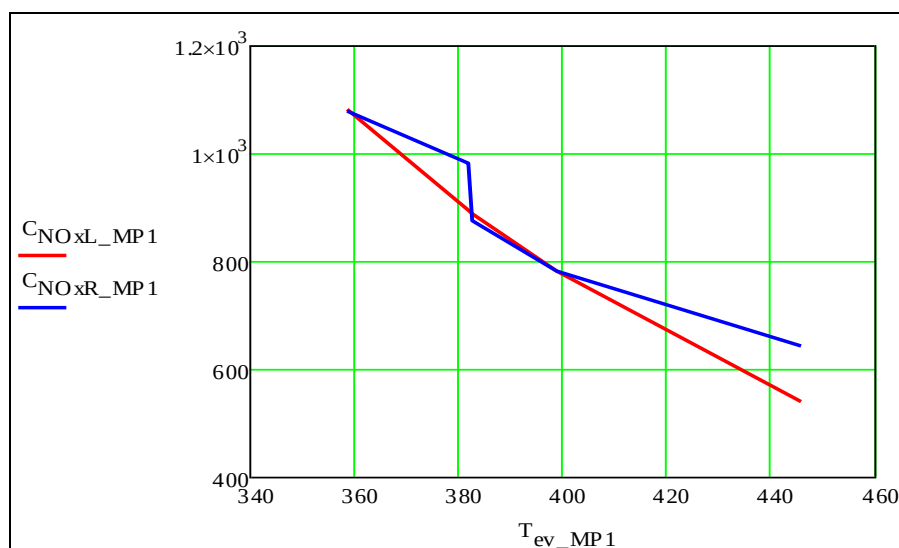


Figure 5. Comparison of the real variation of NO_x concentration with the calculated variation, for the main engine

4.2. Observations concerning the analytical determination method

The analytical method of determination can be used when the variation of the real measured parameters is linear or parabolic. In other situations it is necessary to make the calculated values linear first and to approximate some values, so one will obtain errors over the admissible margin, and the formulas can't be validated any more.

This is why, in the framework of determinations based on the evolution of the functional parameters, we are going to use the graphical method.

4.3. The graphical method of determining concentrations

The graphical method is based on the construction of the diagrams of variation of concentrations that are necessary to be determined depending on the functional parameters of the engine. Thus, by using the data of the measurements undertaken at the ship's release from the shipyard, one may determine the variation diagrams of the concentrations depending on different parameters. In these diagrams, by introducing the parameters measured onboard the ship one shall determine the pollutant component concentration. Depending on the influence of diverse parameters on the pollutant component concentrations, we chose the following diagrams.

But in order to trace these diagrams, one shall use the following simplifying hypothesis: one considers that a certain pollutant component concentration varies only depending on one single functional parameter of the engine. In reality the emissions variation depends on more than one functional parameter.

Using this simplifying hypothesis and the graphical method of determining emissions allows us to easily determine the values of the specific emissions. After determining these values, one may determine those parameters of the engine that influence the values of the emissions.

Therefore, the use of the graphical method may lead to the apparition of some errors in determining the exact values of the emissions concentrations, but in the absence of gas analysers, the method becomes useful. On the other hand the errors that might be obtained would not affect the manner of appreciation of the impact of some parameters over emissions.

Table 8. Parameters used in the analytical method

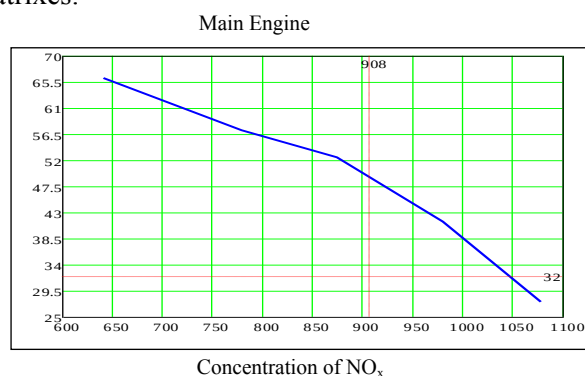
MP	$C_{NOx}=f(F_{cmd})$	$C_{CO}=f(F_{cmd})$	$C_{CO2}=f(F_{cmd})$	$C_{O2}=f(F_{cmd})$	$C_{HC}=f(F_{cmd})$
DG	$C_{NOx}=f(n_{TS})$	$C_{CO}=f(n_{TS})$	$C_{CO2}=f(n_{TS})$	$C_{O2}=f(n_{TS})$	$C_{HC}=f(n_{TS})$
PP	$C_{NOx}=f(T_{ge})$	$C_{CO}=f(T_{ge})$	$C_{CO2}=f(T_{ge})$	$C_{O2}=f(T_{ge})$	$C_{HC}=f(T_{ge})$

where:

- C_{NOx} – concentration of NO_x [ppm];
- C_{CO} – concentration of CO [ppm];
- C_{CO2} – concentration of CO_2 ;
- C_{O2} – concentration of O_2 ;
- C_{HC} – concentration of HC;
- F_{cmd} – fuel order of the main engine [%];
- n_{TS} – speed of the turbo blower from the diesel generator [rpm];
- T_{ge} – temperature of the exhaust gases of the cargo pumps engine [$^{\circ}C$];

Further on we present the diagrams that will be used for determining concentrations. All these diagrams have been realised with the data obtained at the release of the ship from the shipyard.

The diagrams have been realised with the aid of the MathCAD program, in which parameters have been defined as column matrixes.

**Figure 6.** The diagram of determining the Concentration of NO_x for the Main Engine

5. Conclusions

In this paper two methods of determination of the pollutant emissions are presented: an analytical one and a graphical one for a ship, in order to establish if the level of emissions is placed within the limits imposed by the international norms, valid for any type of propulsion based on an engine with internal combustion regardless of its type (functioning with Diesel fuel, LNG, LPG, piloted injection or any other type). In this category are also included ships with azimuthal propulsion and a diesel – electrical propulsion.

Given the rules established on an international level by the MEPC and on an European level through directives like the Directive 2012/33/EU, the necessity of the emissions evaluation, monitoring and control becomes of an immediate importance, taking into account the fact that at the current time the emissions and the type of fuel are strictly monitored in European harbours and over the next two years attention of the maritime authorities in this respect is to be extended to the territorial waters or in the exclusive economical areas.

Furthermore, a viable method of monitoring emissions on board ships proves to be a valuable instrument for monitoring the degree of implementation of the Ship Energy Efficiency Management

Plan and the manner of BRM with the second level of implementation of the EEDI, both going into effect.

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