Numerical methods for assessment of the ship’s pollutant emissions

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Abstract. The maritime transportation sector constitutes a source of atmospheric pollution. To avoid or minimize ships pollutant emissions the first step is to assess them. Two methods of estimation of the ships’ emissions are proposed in this paper. These methods prove their utility for shipboard and shore based management personnel from the practical perspective. The methods were demonstrated for a product tanker vessel where a permanent monitoring system for the pollutant emissions has previously been fitted. The values of the polluting agents from the exhaust gas were determined for the ship from the shipyard delivery and were used as starting point. Based on these values, the paper aimed at numerical assessing of ship’s emissions in order to determine the ways for avoiding environmental pollution: the analytical method of determining the concentrations of the exhaust gas components, by using computation program MathCAD, and the graphical method of determining the concentrations of the exhaust gas components, using variation diagrams of the parameters, where the results of the on board measurements were introduced, following the application of pertinent correction factors. The results should be regarded as a supporting tool during the decision making process linked to the reduction of ship’s pollutant emissions.

1. Introduction
The emissions generated by this sector are not appropriately regulated at international level, but this problem is now under debate at the International Maritime Organization (IMO) and The United Nations Framework Convention on Climate Changes (UNFCCC). With regards to the greenhouse effect gas (GHG – Green House Gas) emissions, the maritime transportation is the most ecological means of transportation [1].

The contribution of marine transport to global NOx emissions attributed to ships is about 15 % of the global emissions [2]. International Maritime Organization defines the amount of nitrogen oxides (NOx) that a ship is permitted to release. This amount varies for different ships and navigation areas, the limits being set for nitrogen oxides emissions dependent of diesel engine maximum operating speed. The limits are specified in three levels, named Tiers, according to the date of the ship’s construction as specified in table 1[3]. The limits for Tier I and Tier II are global while the standard for Tier III is applicable only for the vessels navigating into NOx Emission Control Area (NECA) [4,5].

The above mentioned limits are illustrated into figure 1 for different values of the engines rated speed, in order to emphasize the international standard elaborated by IMO and included in the International Convention on the Prevention of Pollution from Ships, MARPOL 73/78, Annex VI. This annex aims at reduction of ships pollutant emissions by the introduction of stringent emissions limits.
in Emission Control Areas to reduce the sulphur oxide and nitrogen oxide emissions of ocean-going vessels.

Table 1. Limits for the nitrogen oxides emission [3].

| Tier | Ship construction date on/after | Total weighted cycle emission limit (g/kWh) |
|------|---------------------------------|--------------------------------------------|
|      |                                 | n= engine’s rated speed (rpm)               |
|      |                                 | n < 130  | n = 130-1999  | n > 2000 |
| I    | 1st of January 2000             | 17       | 45.n^{-0.2}    | 9.8     |
| II   | 1st of January 2011             | 14.4     | 44.n^{-0.23}   | 7.7     |
| III  | 1st of January 2016             | 3.4      | 9.n^{-0.2}     | 2       |

Figure 1. IMO requirements for NOx emissions [6].

2. Case study
The determinations and the calculations undertaken within the framework of this section have at their base functional parameters of the installations on board M/T Aristidis [7]:

- Deadweight 37 000
- Main engine type DU Sulzer 6 RT Flex 50,
- Three diesel generator sets Hyundai – Himsen two type 6H21/32 and one 5H21/32, and
- Two auxiliary engines pertaining to the cargo pumps type Cummins KTA 19-D(M) [5].

The ship’s characteristics are: length between perpendiculars 183 m, beam 32.2 m, maximum speed 15.7 Knots.
3. Numerical methods
In order to determine the specific values of the exhaust gas emissions (in g/kWh), it is necessary first of all to determine the concentrations of the exhaust gas components. Most often, these are determined through direct measurement. In case there is no means of direct measurement, analytical approximation methods have to be used.

Thus, the authors propose two methods for the emissions concentration determination with the purpose of establishing if the level of emissions lays within the limits imposed by the international norms and applicable to other type of propulsion based upon an internal combustion engine, regardless of what type it actually is (with functioning on Diesel fuel, LNG, LPG, piloted injection or any other type).

The two methods refer to:
- The analytical method of determining the concentrations of the components within the exhaust gas, utilising a calculation program that is realized in MathCAD, using as entry dates the results obtained in the measurements undertaken at the vessel’s delivery from the shipyard;
- The graphical method of determining the concentrations of the components of exhaust gas, by utilising diagrams of the parameters variations. The method uses the results from the measurements undertaken at the ship's exit from the shipyard.

4. Assessment of the pollutant emissions of NOx

4.1. Analytical method
For the determination of the NOx concentration, the temperature of the exhaust gas before the turbine (Tev), has been selected as calculation parameter. The real value of the NOx concentration (CNoxR) was determined for the main engine, during trial shipyard measurements:

| Exhaust gas temperature before turbo charger | Tev [degC] | 359.0 | 382.0 | 383.0 | 399.0 | 446.0 |
|----------------------------------------------|------------|-------|-------|-------|-------|-------|
| Concentration of dry NOx CNoxR [ppm]         |            | 1079.0| 981.0 | 875.0 | 780.0 | 641.0 |

The variation the NOx concentration, real values (CNoxR) has been determined as difference between the maximum and minimum values:

$$D_{\text{NOxR MP}} = C_{\text{NOxR MP}}^{(\phi)} - C_{\text{NOxR MP}}^{(\phi)}$$

Due to the fact that the ship trials results are affected by the uncontrollable environmental conditions, there is an area of uncertainties to the measurements errors [8,9]. Therefore, to estimate the NOx concentration, calculated values (CNoxL), the authors have used a mathematical algorithm for determination of the coefficients and exponents. The coefficients and the exponents have the following values:
- Coefficient for determining the exponent of result, xMP = 100;
- Exponent for adjustments of the minimum and maximum values of concentration, yMP=4.74885;
- Exponent for computer graphic, zMP=2.5;
- Coefficient for correction of the minimum value of concentration, mMP=22.39.

After the procedure of determining the calculation formula, the following errors were obtained:
Table 3. Error determination.

| ED_Mp | EM_Mp | E0_Mp | E1_Mp | E2_Mp | E3_Mp | ΔEMP | ED_Mp |
|-------|-------|-------|-------|-------|-------|-------|-------|
| 1     | 0.006 | 0.006 | 8.884 | 1.333 | 0.012 | 1.883 | 1     |

The obtained values for errors are acceptable and the determination ratio is equal to 1.

\[ C_{NOxL\_MP1} = \frac{y_{MP}^{z_{MP}^{3}}} {T_{ev\_MP1}^{y_{MP}}} - \frac{1000m_{MP}}{y_{MP}^{3}} \]  \[ \text{[ppm]} \]  \[ (2) \]

By introducing the coefficients and exponents into the calculation formula, equation 2 it has been possible to determine the NOx concentration in ppm (CNoxL), for the same values of the temperature of the exhaust gas before the turbine (Tev).

The real results of the measurements and of applying the analytical algorithm are emphasized into the graphic comparison of the real variation of NOx concentration (CNoxR), with the calculated value for the main engine (CNoxL), as presented below at Figure 2:

![Figure 2](image)

**Figure 2.** The real variation of NOx concentration compared with calculated variation, for the main engine.

4.2. Graphical method

The graphical method is based upon the construction of variation diagrams that show the concentrations required to be determined according to the functional parameters of the engine. Thus, by utilising the data of measurements from the exit of the ship from the shipyard, one may determine the variation diagrams of the concentrations according to different parameters. Within these diagrams, by introducing the parameters measured on board the ship, one may determine the concentration of the pollutant component. In accordance with the influence of various parameters upon the component pollutant concentrations, we have chosen the realisation of the diagrams presented in figures 3, 4, 5 and 6.
In order to trace these diagrams, the following simplifying hypothesis may be utilised: one considers that a certain concentration of pollutant component varies only according to a functional engine parameter. In reality the emission variation is a function of more than one functional parameters.

The utilisation of this simplifying hypothesis and of the graphical method of emissions determination allows us to easily determine the specific values. After settling these values, one may determine those engine parameters that influence the emission values. These parameters are subject to further study.

The utilisation of the graphical method, may lead to the emergence of determination errors for exact concentrations of the emissions values, but in absence of gas analysers, the method becomes useful. On the other hand, the errors that may result would not affect the manner of appreciation of the impact of parameters upon the emissions.

The diagrams utilised for the determining of concentrations, i.e. the diagrams of determining of the NOx concentration, are presented below. These diagrams have been realised with the data obtained when the ship was taken out of the shipyard by using the MathCAD.

**Figure 3.** Determination of NOx concentration [ppm] for Main Engine DU Sulzer 6 RT flex 50 as per fuel index[%].

**Figure 4.** Determination of NOx concentration [ppm] for diesel generator sets (6H21/32) as per turbocharger speed [rpm].

**Figure 5.** Determination of NOx concentration [ppm] for diesel generator sets (5H21/32) as per turbocharger speed[rpm].

**Figure 6.** Determination of NOx concentration [ppm] for auxiliary engines (Cummins KTA 19 - D (M)) as per exhaust gas temperature [degC].
5. Conclusions
The analytical determination method may be utilised, where the variation of the real measured parameters is linear or parabolic. In the other situations, the linearization of the calculated values is necessary and also value approximation. Errors above the admissible limitation may be obtained and the formulas can no longer be validated.

Due to this reason, within the framework of the determinations based upon the evolution of functional parameters one has utilised the graphical method. By analysing the obtained graphical results with the simulation program presented within this study, it can be notice that the highest values of the NOx concentration correspond to the areas in which the temperature surpasses the value of 2000K, the reason being the mechanism of NOx formation.

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