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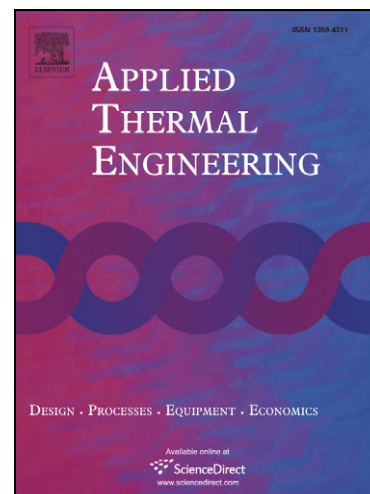
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## NO<sub>x</sub> emission from a two-stroke ship engine: Part 2 – laboratory test

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### Abstract

International regulations forces ship owners to monitor the NO<sub>x</sub> emission from engines during sea operational use of ships, but standard equipped engine rooms has not installed any measurement equipment to analyze of exhaust gases. According to these regulations we proposed a simple method to estimation of NO<sub>x</sub> emission without direct measurement, based on the measurements of working engine parameters. In this paper we present the effect of laboratory test to verification adequacy of the developed model. In this aim we carried out tests on the two-stroke, one-cylinder, loop scavenged diesel engine. During tests the engine operated with the various rotational speed, load and changing air/fuel equivalence ratio. The comparison of the results of calculations with conducted tests showed the estimation errors in intervals 1,8 to 11% in dependence from the substitute molar compositions of fuels.

Keywords: NO<sub>x</sub>; Emission; Engine; Ship; Modeling; Two-Strike

### 1. Introduction

Nitrogen and oxygen with a different atomic composition are elements combine to form various chemical compounds called the nitric oxides (NO<sub>x</sub>). Most concentrations of all emitted from diesel engines NO<sub>x</sub> have two such chemical compounds: nitric oxide (NO) and nitric dioxide (NO<sub>2</sub>) [1]. International Maritime Organization (IMO) developed in 1997 *Annex VI* to MARPOL 73/78 convention and its integral part *Technical Code on Emission of Nitrogen Oxides from Marine Diesel Engines* in order to prevent the negative influence of these compounds on the environment and on health [2], [3]. The NO<sub>x</sub> emission limits are related to engine crankshaft speed and equal from 9,8 g/kWh for rotational speed above 2000rpm to 17g/kWh for rotational speed less than 130 rpm. After ratification, these documents entered into force in 2005.

The *Annex VI* forces ship owners to monitor the NO<sub>x</sub> emission from ship engines whereas *Technical Code* determines its allowable level. Moreover, regulations contained in the *Annex VI* oblige ship owners to verify the required emission level. According to these regulations:

- each of ship engines should receive a certificate confirming compliance with the specified requirements and the allowable errors of emission measurements can reach up 10% in a case of using a diesel fuel and 15% in a case of a heavy fuel oil,
- an emission level of NO<sub>x</sub> should be verified by direct measurements carried out during a ship operational use.

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The last regulation obliges ship owners for temporal withdrawing the certificated ship from operation and to install the additional measuring equipment on its onboard enabling for the direct measurement. Therefore, it appears the need to develop an effective and simple method allowing for estimating the NO<sub>x</sub> emission level from ship engines, which should be in accordance with the existing regulations. Moreover, such a method should not entail the necessity of withdrawing ships from their operation use for time of carrying out the required measurements and installing costly measuring apparatus.

In our opinion, the presented conditions would accomplish a method based on a model of NO<sub>x</sub> formation in an engine combustion chamber. Therefore, we developed the NO<sub>x</sub> concentration model in exhaust gas emitted from a two-stroke ship engine. It consists of both the thermodynamically model of a combustion process and the kinetic model of chemical reactions taking place during an engine working process. Application of such method does not require carrying out direct measurements of engine exhaust gases by exhaust gas analyzers. For the developed method, results of engine working parameters should be sufficient (i.e. rotational speed of the engine, fuel consumption, thermodynamic parameters of air and fuel, measured pressure in the combustion chamber). Moreover, such results can be obtained by using of measuring devices installed in the standard equipped engine room.

Taking into account wideness of the considered issue, we bounded for developing the appropriate model applicable only for the two stroke, large, loop scavenged engine. Such a type of engine is widely used in vessel propulsion. Specific design and working parameters of these engines set up different conditions of the NO<sub>x</sub> formation in relation to shore engine applications, for example car engines. Large dimensions of the cylinder of ship two-stroke engines and multiple less rotational speed causes long time of burning process in high temperature and pressure conditions. In these case, well-known simple models for predicting the NO<sub>x</sub> emission i.e. Zeldowicz's model makes very problematical to adapt the computational algorithms from the engines without considering another reactions of burning process.

A computational algorithm enabling to assess the NO<sub>x</sub> concentration based on the mentioned model. All necessary data for this assessing should be received by means of:

- measurements of working parameters of the ship engine,
- analysis of the accessible design documentation of the ship engine,
- analysis of parameters characterizing a composition of fuel used by the considered ship engine.

Due to the hybrid form of the developed model, all measurements of engine working parameters should be obtained directly during the normal engine operation use. In order to decrease the cost of such kind of research, we decided to carry out it in laboratory conditions. The main purposes of the laboratory test were:

- carrying out of the direct assessment of the NO<sub>x</sub> concentration in the exhaust gases of the tested engine by means of using an analyzer of exhaust gas,
- determining of the NO<sub>x</sub> concentration in the exhaust gases of the tested engine by means of using the developed computational algorithm,
- verification of the developed model adequacy.

The carried out test allows to obtain values of the NO<sub>x</sub> content in the working engine exhaust gases measured directly by the combustion gas analyzer and values of engine working parameters enabling to calculate the NO<sub>x</sub> content in the tested engine exhaust gases by means of the developed computational algorithm. The issues of modeling, can be found in [4].

In this paper, the selected results of the NO<sub>x</sub> concentration in the exhaust gases for the tested engine obtained by both the direct assessment and the computational algorithm are presented. Moreover, the comparison of these results obtained by both the direct assessment and the computational algorithm are described as well.

## 2. Description of the laboratory stand

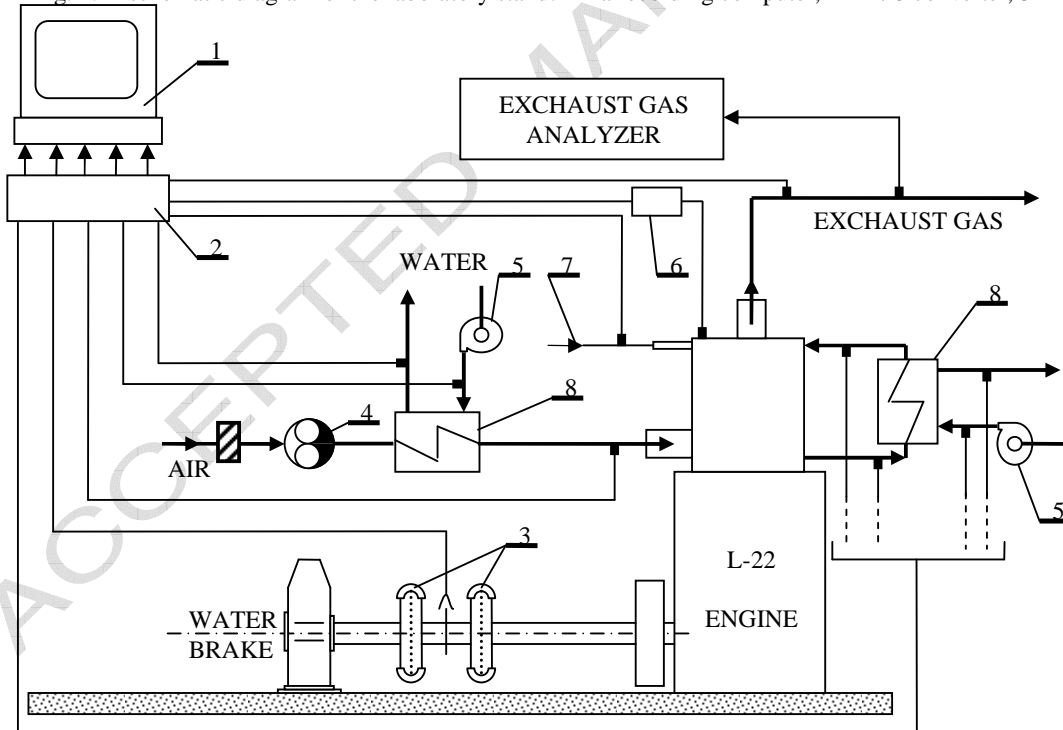
We have carried out the laboratory test using the engine L-22 installed in Gdynia Maritime University laboratory. It is a crosshead, single-cylinder, and two-stroke diesel engine with loop scavenging. Roots' blower driven independently by an electric motor with an infinitely variable adjustment of rotational speed charges this engine. The tested engine is loaded by a water brake. Basic parameters of the L-22 engine are presented in Table 1. and a schematic diagram of the laboratory stand is presented in Figure 1.

Table 1. Parameters of the test engine

Nominal Power [kW]	73,5
Rotational Speed [rpm]	600
Cylinder bore [mm]	220
Piston Stroke [mm]	350
Compression Ratio [-]	18,5
Fuel consumption at maximum load* [kg/h]	7,33
Specific fuel consumption at maximum load* [g/kWh]	277,6

\* – maximum load considered during laboratory tests (see description below)

Fig. 1. A schematic diagram of the laboratory stand: 1 – a recording computer, 2 – A/C converter, 3 –



rubber flexible couplings, 4 – Roots' blower, 5 – a fresh water pump, 6 – an electronic indicator of pressure, 7 – fuel installation, 8 – a heat exchanger

The measuring equipment installed on the tested engine permitted on the continuous recording of the most measured results with samplings approximately 0,5 second. We have measured the following engine working parameters:

- the rotational speed of the engine and Roots' blower,

- the viscosity and fuel temperature,
- the temperature and pressure of lubricating oil on the inlet and outlet of the engine,
- the cooling water temperature and pressure on inlet and outlet of the engine,
- the temperatures, pressures and humidity of the scavenging air,
- the quantity of a torque of the engine,
- the fuel consumption,
- the volume of charging air flow.

Moreover, during this research have been recorded the following additional parameters:

- the profile of pressure in the combustion chamber of the tested engine with using an electronic indicator,
- the composition of combustion gases, the surrounding temperature, and the temperature and pressure of combustion gases with using the electrochemical analyzer of combustion gases.

According to the part-1 of the paper the quantity of NO<sub>x</sub> emitted from engine depends on temperature and pressure of combustion, time of combustion and composition of combusted mixture. The temperature and pressure of combustion is determined by load of the engine (with the same adjusted parameters like angle of injection, timing of exhaust valve, capacity of cooling system) and changing the load of the engine causes changes of temperature and pressure of combustion. Time of combustion is determined by speed of the engine. In the same timing of the exhaust valve, increasing of speed of the engine causes decreasing of combustion time. Composition of mixture is changed by changing the air/fuel equivalence ratio with the same combusted fuel.

The fundamental stage of our research consists of 10 observations. We loaded the tested engine in a range from 25% to 65% of its nominal load with two rotational speeds namely 200 and 360 rpm. The larger load of the engine was not possible because of the admissible load of the used water brake and too small efficiency of the Roots' blower for keeping of steady air/fuel equivalence ratio. The measurements have been carried out for the working engine with:

- its constant rotational speed and changeable loads for a constant value of air/fuel equivalence ratio,
- its constant rotational speed and load for changeable values of air/fuel equivalence ratio.

In this research, the air/fuel equivalence ratio [5] was understood as a ratio of a mass amount of air delivered to a cylinder to amount of air necessary to combustion of a fuel dose injected to this cylinder whereas the changeable loads realized by means of using a water brake. Values of the engine loads ( $M$ ) described like percent of nominal momentum  $M_n$  and rotational speeds ( $n$ ) are presented in Table 2.

Table 2. Values of the tested engine loads and rotational speeds

No.	1	2	3	4	5	6	7	8	9
$M$ [% of $M_n$ ]	65	60	55	50	45	40	35	30	25
$n$ [rpm]	200								
No.	10	11	12	13	14	15	16	17	18
$M$ [% of $M_n$ ]	65	60	55	50	45	40	35	30	25
$n$ [rpm]	360								

During our research, the engine has been supplied by the diesel fuel with its known specification obtained from its producer (Lotos EuroDiesel EKO Z with density at 15°C equal 829,6 kg/m<sup>3</sup>). Nevertheless, for the assessment of the NO<sub>x</sub> emission by using the computational algorithm, we assumed composition of fuel after its vaporization and thermal decomposition as a mixture of simple hydrocarbon ions and general relation between a carbon and hydrogen atoms for diesel fuel oils CH<sub>1,8</sub>. Data for this mixture have been taken from [5] and [6]. The substituted molar composition of the considered substitute fuels are presented in Table 3.

Table 3. Substitute molar compositions of fuels

Type of fuel	Mole fractions [-]			
	CH	C <sub>2</sub> H <sub>2</sub>	CH <sub>2</sub>	CH <sub>3</sub>
I	0,3	–	0,6	0,1
II	0,4	–	0,4	0,2
III	0,5	–	0,2	0,3
IV	–	0,3	0,6	0,1
V	–	0,4	0,4	0,2
VI	–	0,5	0,2	0,3

### 3. Effect of the engine working parameters on the NO<sub>x</sub> mole fractions

The carried out test allows to obtain:

- values of the NO<sub>x</sub> content in the working engine exhaust gases measured directly by means of the combustion gas analyzer,
- engine working parameters enabling to calculate the NO<sub>x</sub> content in the tested engine exhaust gases by means of the developed computational algorithm.

In the mentioned approaches, the NO<sub>x</sub> content in molar concentration was expressed in *particle per million* (ppm) units. It was also recognized as a sum of molar concentrations of NO, NO<sub>2</sub> and N<sub>2</sub>O for the crank shaft angle equals 274° from bottom dead center. According to timing of exhaust valve, this angle responds to the point of opening of a combustion chamber. Concentration of others NO<sub>x</sub> compounds did not exceed more than 1% of all NO<sub>x</sub> concentration and therefore they were neglected.

Findings concerning the NO<sub>x</sub> content in the exhaust gases, which have been obtained from both the direct measurements by means of the combustion gas analyzer and the computational algorithm have been collected and presented in the form of collective diagrams.

#### 3.1. Effect of the engine loads on the NO<sub>x</sub> mole fractions

The figure 2 and 3 shows effect of the engine loads on the NO<sub>x</sub> mole fractions for the substitute molar compositions of fuels and the constant engine rotational speed equals  $n = 200$  rpm and 360 rpm accordingly.

Results obtained from the carried out research agreed in principle with the findings presented in the subject literature [7], but NO<sub>x</sub> fractions were smaller than it was expected. The reason of this is the high air concentration after scavenging (air/fuel equivalence ratio equals 4,7). According to the obtained results, the substituted molar composition of the tested fuel is very important for values of the NO<sub>x</sub> mole fractions received by means of the computational algorithm. The comparison between results obtained for all substitute molar compositions of the tested fuel shows that the most representing composition

have the substitute fuels II and V. The analysis of these results obtained only for these two fuels shows that errors did not exceed 1,8% for engine rotational speeds  $n = 200$  rpm and 3,5% for  $n = 360$  rpm, in relation to the measured values of the NOx mole fractions.

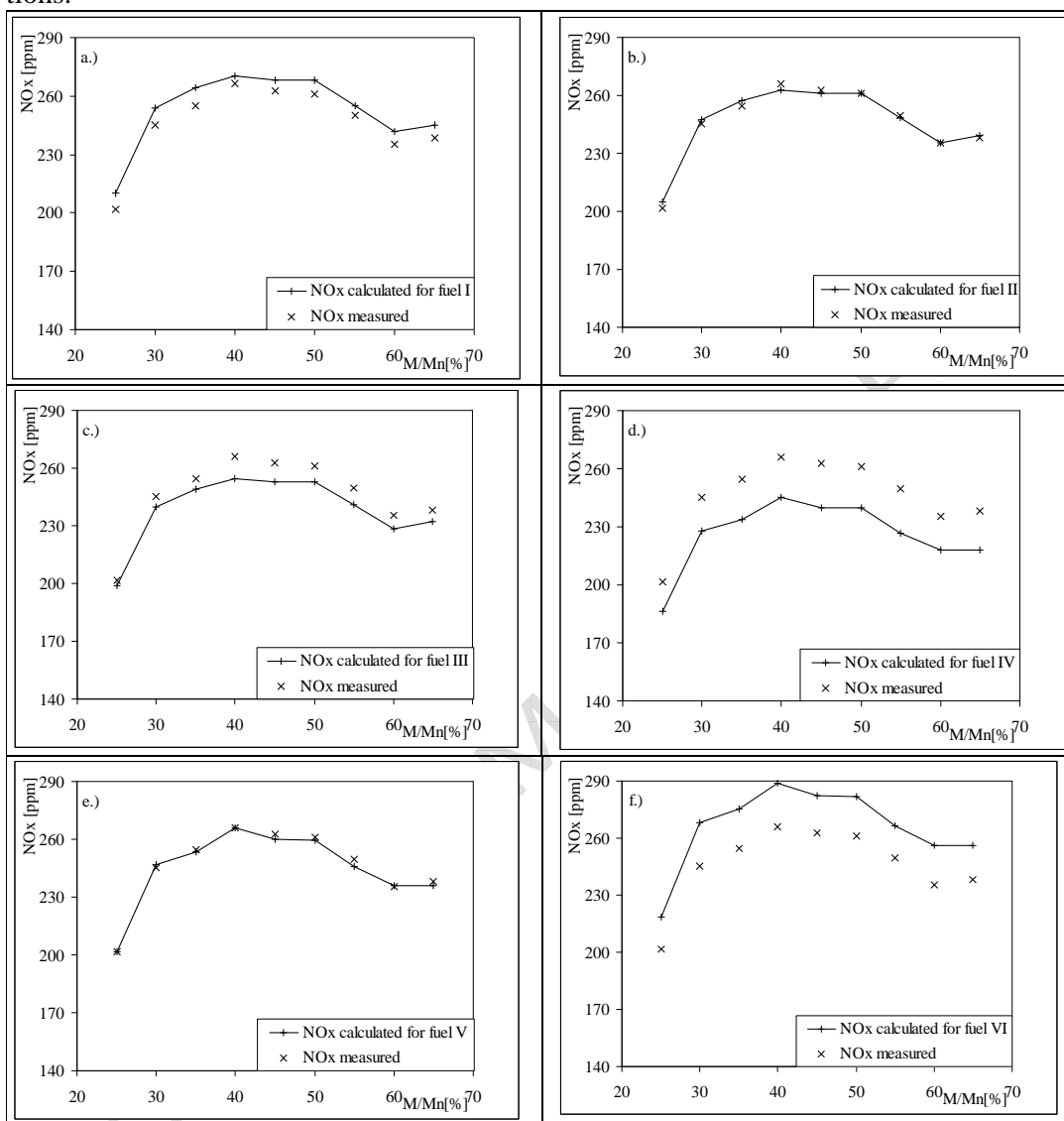
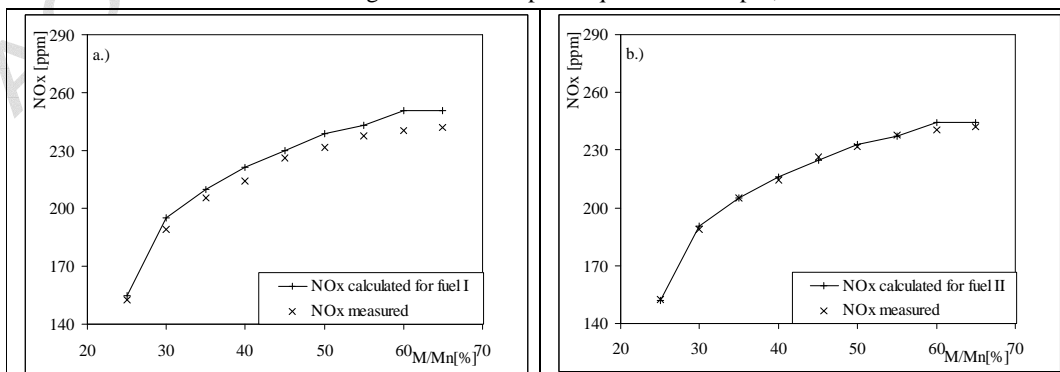


Fig. 2. Effect of the engine loads on the NOx mole fractions for substitute molar compositions of fuels and engine rotational speed equals  $n = 200$  rpm,





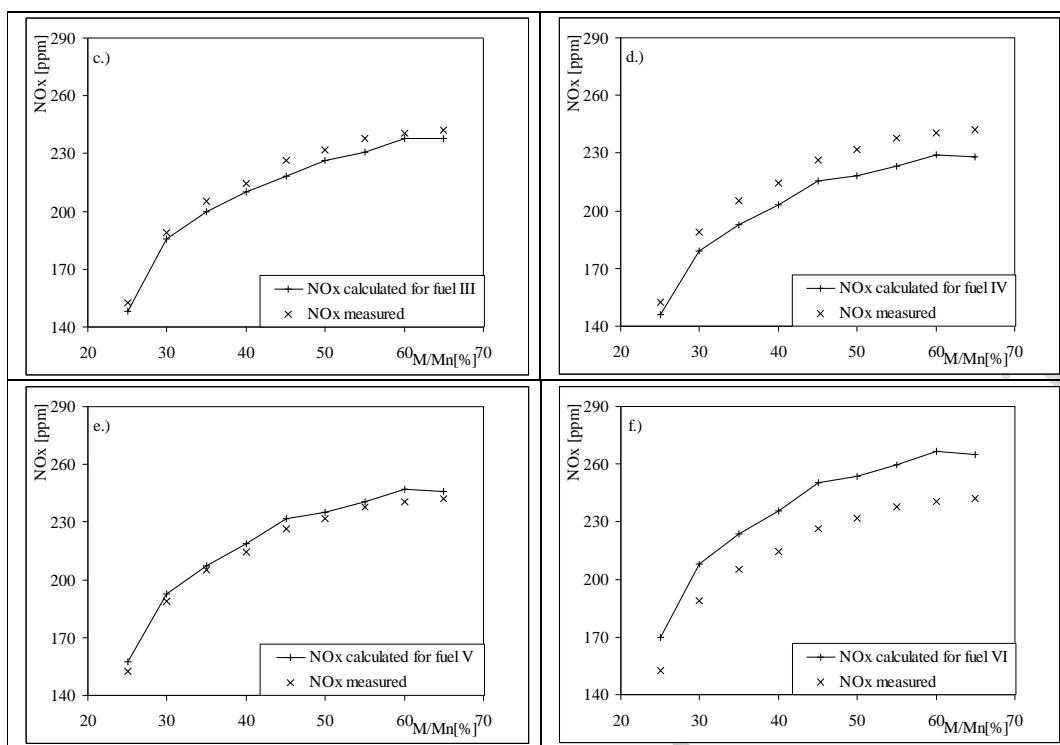


Fig. 3. Effect of the engine loads on the NOx mole fractions for substitute molar compositions of fuels and engine rotational speed 360 rpm,

The maximum values of errors were received for the substitute fuel VI, but only for 25% Mn the engine load for the tested engine work with rotational speed 360 rpm the error exceed above 10% and equals 11,3%. It means that the correct selection of the substitute molar composition of fuel to actually burnt fuel can be fundamental for the correct estimation of the NOx emission level during the sea operation of the engine. Moreover, we noticed also the tendency of increasing the NOx mole fraction together with decreasing the CH ions mole fractions in the substitute fuel I, II and III regardless of the engine load and rotational speed changes. However, in case of replacement of CH ions by C<sub>2</sub>H<sub>2</sub> ones (substitute fuel IV, V and VI), we observed opposite this tendency.

Taking into account regulations Annex VI to MARPOL convention [3], which allow for 10% error, we can state in general that results obtained from measurements and calculations are consistent from this point of view.

### 3.2. Effect of values of the air/fuel equivalence ratio on NOx mole fractions

Results of the NOx mole fractions for the substitute molar compositions of fuels (Fig. 2 and 3) were calculated for a constant value of air/fuel equivalence ratio. Bearing in mind the influence of this parameter on the NOx emission, we calculated values of the NOx mole fraction in exhaust gas for a changeable value of the air/fuel equivalence ratio.

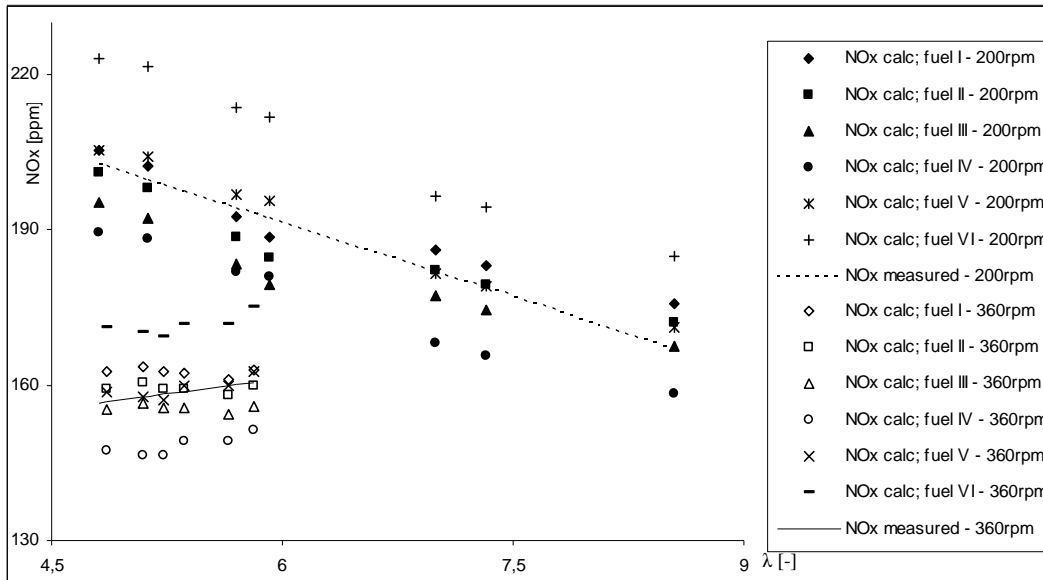


Fig. 4. Effect of values of the air/fuel equivalence ratio on NOx mole fractions for substitute molar compositions of fuels and engine rotational speeds 200 rpm and 360 rpm

Figure 4 shows results obtained from both the direct measurements and the computations of the NOx mole fractions for the changeable values of the air/fuel equivalence ratio. As in the case of the tested engine work with changes of its loads, the most representing composition have the substitute fuels II and V. The analysis of these results obtained only for these two fuels shows that errors did not exceed 4,6 to 6,3% values of medium measurements for all observations carried out for a rotational speed equals 360 rpm and 6,2 to 8,5% a rotational speed equals 200 rpm in relation to the measured values of the NOx mole fractions.

The maximum values of errors were received for fuel VI as well. According to results obtained from both the direct measurements and the computation, the relative increase of air amount delivered to a cylinder expressed in some way by the air/fuel equivalence ratio, causes to decreasing the NOx mole fractions in exhaust gases for the engine work its relatively low rotational speed and to increasing these fractions in the case of its high rotational speed.

#### 4. Conclusions

Results of the NOx concentration in exhaust gas of the tested working engine obtained by both the direct measurements by using of a gas analyzer and the calculation by using the developed computational algorithm allow to draw the following conclusions:

- The results obtained from the direct measurement shows, that the NOx concentration in the exhaust gases of the engine changes together with the change of the engine load. Moreover, the character of these changes depends on the rotational speed of the engine. In these reasons the estimation of the NOx emission level has to be carried out for the various conditions of the engine load.
- the change of load, the rotational speed of the engine and the air/fuel equivalence ratio causes the change of the NOx concentration in exhaust gases measured during tests and calculated also. The character of these changes is similar for the results of calculations and measurements. The results of calculations depend in the large stage on the substitute molar composition of fuel.
- the developed computational algorithm correctly responds on changes of load and rotational speed of the engine and changes of air/fuel equivalence ratio. It means that

the algorithm correctly responds on changing the temperature, pressure and the time of combustion and changing the composition of burned fuel (at considered range) because both temperature and pressure of combustion are determined by the engine load. Changes of the engine load causes to changes of temperature and pressure of combustion whereas time of combustion process is determined by the engine speed. Composition of mixture is changed by changing the air/fuel equivalence ratio with the same combusted fuel. In our opinion, the proposed algorithm is sufficient to assess the NO<sub>x</sub> concentration emitted from the two-stroke ship engine during its operational use according to requirements of Annex VI regulations. However, you should pay attention that the results of calculations strongly depend on the substitute molar composition of fuel. For this reason, it requires more investigations to implement the proposed methodology.

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