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# INFLUENCE OF THE MARINE 4-STROKE DIESEL ENGINE MALFUNCTIONS OF THE AIR AND EXHAUST DUCT ON THE COMPOSITION OF EXHAUST GAS

**Joanna Lewińska**

*Gdynia Maritime University, Department of Engineering Sciences*
*Morska Street 81-87, 81-225 Gdynia, Poland*
*tel.: +48 58 6901331*
*e-mail: j.lewinska@wm.am.gdynia.pl*

***Abstract***

*Malfunctions of an intake air duct and an exhaust gas duct have negative impact on the operation of a diesel engine. The article presents results of a laboratory study on nitric oxides ($NO_x$), carbon monoxide (CO) and carbon dioxide ($CO_2$) emission levels from a marine four-stroke diesel engine. CO and $CO_2$ emission levels are connected with oxygen content and specific fuel consumption. For this reason, the results of the laboratory study present oxygen fraction in exhaust gas and specific fuel consumption. The object of the study was laboratory piston engine, operating at constant speed. The measured engine parameters were carried out according to the regulations of the Annex VI to MARPOL 73/78 Convention. The study consisted of tests during engine operation without malfunctions and engine operation with simulated malfunctions. The laboratory study consisted of 3 observations: the engine assumed as operated without malfunctions, throttling of the exhaust gas duct by rotational barrier about 56° and throttling of the air intake duct by reducing of its cross section area by 60%. The simulated malfunctions caused changes in the total weighted $NO_x$ and CO emissions in all considered engine loads. All simulated malfunctions resulted in a decrease of all mentioned emission levels in the composition of exhaust gases during the operation at low engine loads and an increase of the $CO_2$ emission level at the maximum engine load operation. The oxygen fraction decrease was observed for throttling of the intake air duct. The calculations of the weighted specific fuel consumption present a 2-3% change in the engine efficiency.*

***Keywords:*** *emission, malfunction, marine engine, piston engine, nitric oxides, carbon monoxide, carbon dioxide*

## 1. Introduction

A standard that regulates the permissible emissions of volatile compounds from marine diesel engines is the International Convention for the Prevention of Pollution from Ships MARPOL 73/78 − Annex VI. The subjects of Annex VI to MARPOL 73/78 are in particular nitrogen oxides ($NO_x$), sulphur oxides ($SO_x$), ozone depleting compounds, and volatile organic compounds [6, 10]. On the 1st of January 2013, the International Maritime Organization (IMO) has adopted mandatory measures to reduce emissions of greenhouse gases from international shipping. Chapter 4 "Regulations on energy efficiency for ships" has been added to the Annex VI of MARPOL 73/78. In literature, J.P. Jalkanen et al. present modelling system for the exhaust emissions of marine traffic and its application in the Northern European area [3]. The authors of this article present model for evaluation of the emissions of the $NO_x$, $SO_x$ and $CO_2$. Mentioned model is mainly created of the marine traffic, vessel technical data and the messages provided by the Automatic Identification System (AIS). Standard construction of the engine room has installed on couple of piston engines with nominal power above 130 kW [4]. Typically there are low-speed, two-stroke diesel engines or medium speed, four stroke engines operating at a constant speed with variable pitch propeller [4]. One of this diesel engine installed of the engine room is used for propulsion. Also in the ship engine room, we can find 2 or more power generators and one emergency power generator [4]. As it was mentioned before in [4], engine generators occur like medium speed, four-stroke diesel engines operating at a constant speed. Proper operation of all functional systems and their interaction perform marine diesel engine operation. It is required that an engine's operation is reliable and cost-effective [5]. The complicated combustion fuel process results in formation toxic compounds in exhaust gases marine diesel engines. A. Sarvi et al. present [7-9] works about emissions from large-scale medium-speed diesel engines with technical parameters similar to marine diesel engines. Three strategies: engine modifications, fuel composition modifications or exhaust gas treatment can be used for reducing emissions from engines [7]. For example, switching from heavy fuel oils to light fuel oils for certain engine will give lower emissions of CO, $NO_x$ and particulate matter [8]. Furthermore, the Common Rail technology is engine modification depends on control of the fuel injection. The first 4-stroke diesel engine with common rail system has been installed on the ship in 2001 [4]. A. Sarvi et al. present [9] effect of direct water injection and common rail system on the emissions from large-scale medium- speed turbo-charged diesel engines. The diesel engine operating with direct water injection and common rail mode, $NO_x$ emissions decrease by 50% [9]. The common rail system decreases the fuel consumption, while for common rail and direct water injection the fuel consumption slightly increases [9].

Malfunction of the engine and its components can cause excessive emissions of toxic compounds included in the marine diesel engine's exhaust gas. The regulations of Annex VI of MARPOL 73/78 foresee emergencies of the engine and its components [2, 10]. When an emergency malfunction of the marine diesel engine or its components is detected, it should be removed as soon as possible. Irregularities resulting from malfunctions may lead to changes in the composition of exhaust gas. A regular inspection of data concerning emission levels of volatile compounds in the exhaust gas allows detecting the first symptoms of malfunctions in the marine diesel engine and its components.

The target of this study was to explored disturbances in a proper operation of the air exhaust gas exchange system for composition of exhaust gas. The operation of the air exhaust gas system is responsible for appropriate air delivering and removing of exhaust gas after combustion cycle [5]. Mentioned disturbances were obtained by simulation of malfunctions of the exhaust and intake duct throttling in the laboratory marine 4-stroke diesel engine.

## 2. Laboratory test

The object of the study is 3-cylinder, four-stroke marine diesel engine with direct fuel injection, installed in the Internal Combustion Engines Laboratory at the Gdynia Maritime University. The engine is supplied by diesel oil. The object of the study is presented in [4]. The test stand can measure all parameters necessary to determine $NO_x$, CO, $CO_2$ emissions from the engine in accordance with the ISO 8178 standard regulation. The composition of exhaust gas is measured by an electrochemical gas analyser with infrared $CO_2$ sensor [4]. The Tab. 2 present parameters and accuracy measurement electrochemical gas analyser MRU 92/3 D. A diagram of the measuring test stand is presented in Fig. 1 and the parameters of the research object are included in Tab. 1. The purpose of the study was to measure the impact of simulated malfunctions of the engine on $NO_x$, CO, $CO_2$ emissions. CO and $CO_2$ emission levels are connected with oxygen content and specific fuel consumption. For this reason, the results of the laboratory study measure the oxygen level in exhaust gas and specific fuel consumption.

*Tab. 1. Parameters of the Sulzer Al 25/30 engine [4]*

| Parameter | Value | Unit |
|---|---|---|
| Max. electric power | 250 | kW |
| Rotational speed | 750 | rpm |
| Cylinder number | 3 | - |
| Cylinder diameter | 250 | mm |
| Stroke | 300 | mm |
| Compression ratio | 12.7 | - |

*Tab. 2. List of parameters electrochemical gas analyser MRU 92/3 D*

| Parameter | Unit | Measurement range | Measurement accuracy |
|---|---|---|---|
| Air temperature | °C | −20-+120 | ± 2°C |
| Exhaust gas temperature | °C | 0-850 | ± 2°C |
| Carbon monoxide | ppm | 0-8000 | ± 5% |
| Nitric oxide | ppm | 0-4000 | ± 5% |
| Oxygen | % | 0-21 | ±0.2 % |

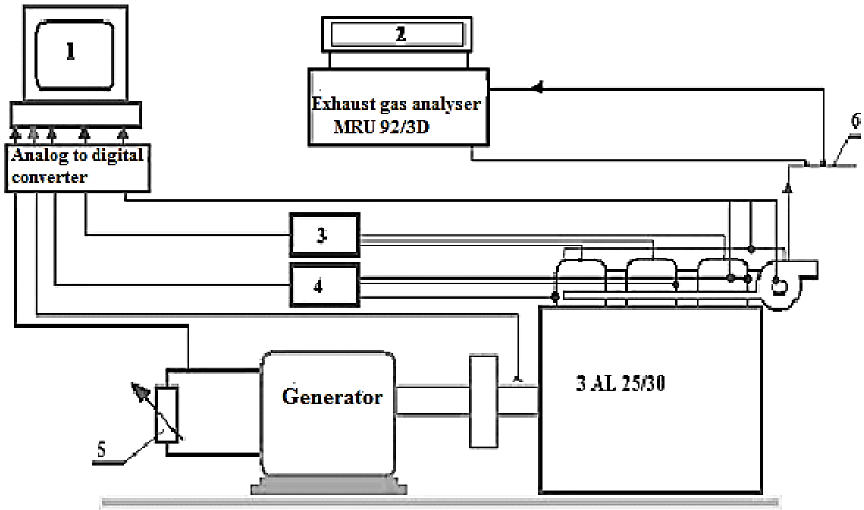


*Fig. 1. The laboratory stand diagram elaborates [4]: 1 – computer – recorder, 2 – exhaust gas analyser 3 – combustion pressure indicator, 4 – injection pressure indicator, 5 – water resistance, 6 – exhaust duct*

Laboratory studies were carried out according to the E2 test cycle [2, 10]. The mentioned cycle is intended for main propulsion engines operating with pitch propeller. Load, engine speed, order of measurements and weight factors for this cycle are presented in Tab. 3 [4].

*Tab. 3. E2 cycle engine adapter to the laboratory engine according [2, 6]*

| **Number of measurement** | **1** | **2** | **3** | **4** |
|---|---|---|---|---|
| Electric power [kW] | 240 | 180 | 120 | 60 |
| Rotational speed [rpm] | 750 | 750 | 750 | 750 |
| Weight factor $W_i$ | 0.2 | 0.5 | 0.15 | 0.15 |

Laboratory study consisted of 3 observations:
- the engine assumed as operated without malfunctions,
- throttling of the exhaust gas duct by changing position of rotational barrier about 56°,
- throttling of the intake air duct by reducing the cross section area by 60%.

Rotational barrier, presented in [4] throttles the exhaust gas duct. Selected angular position of the barrier is 56 degrees in relation to the exhaust gas duct axis [4]. Cross section of the throttling in the inlet and exhaust duct was constant for the all mentioned the engine loads [4].

## 3. Results and discussion

A method of calculating the total weighted $NO_x$ emission is shown in [4]. This article contains calculations and the results of the total weighted emission of CO and $CO_2$ in accordance with the following formula 1:

$$E_{NO_x,CO,CO_2} = \frac{\sum_{i=1,2,...}^{i=n} M_i \cdot W_i}{\sum_{i=1,2,...}^{i=n} P_i \cdot W_i} \left[{}^{g}/_{kWh}\right], \tag{1}$$

where:

$E_{NO_x, CO, CO_2}$ – the total weighted $NO_x$, CO, $CO_2$ emission in [g/kWh],
$M_i$ – the $NO_x$, CO, $CO_2$ emission for i-th phase of the measurement cycle in [g/h],
$W_i$ – the weight factor for the i-th phase of the measurement cycle [Tab. 3],
$P_i$ – the engine power for the i-th phase of the measurement cycle in [kW].

An additional parameter allowing for the determination of the effects of simulated malfunctions on the composition of emitted exhaust gas was air-fuel excess ratio (λ). The value of λ was determined jointly for the whole volume of the exhaust gas flow. It should be noted that, during the combustion of fuel in the cylinders λ varies in time and space. Normally the mole fraction of oxygen in the air is 21 % λ was determined on the basis of the following formula:

$$\lambda = \frac{21\%\ O_2}{21\%\ O_2 - U_{O2}} [-], \tag{2}$$

where:

21% $O_2$ – the mole fraction of oxygen in the air,
(21% $O_2$ – $U_{O2}$) – the amount of air (oxygen) consumed during the combustion.

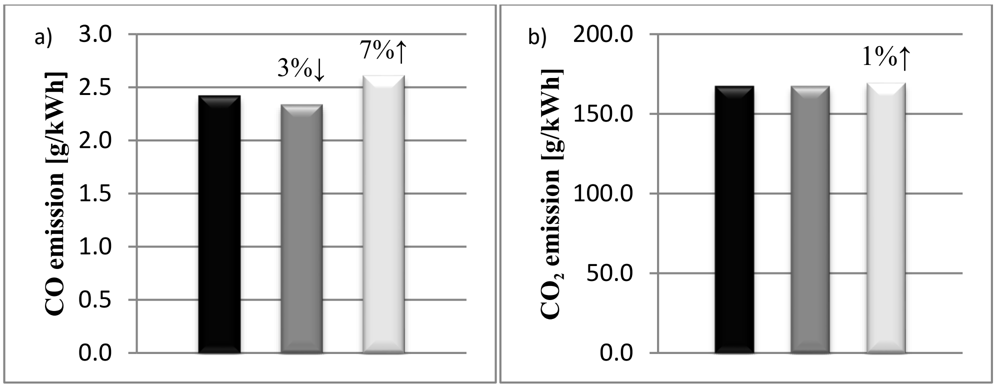


*Fig. 2. The values of the total weighted CO, $CO_2$ emissions: ■ − engine assumed as operated without malfunctions, ■ − throttling of the exhaust gas duct, □ − throttling of the intake air duct*

Figure 2a and b present the percentage change of the total weighted CO, $CO_2$ emission compared to the CO, $CO_2$ emission from the engine assumed as operated without malfunctions. According to presented results in [4], all simulated malfunctions reduce the amount of the weighted $NO_x$ emission by 2-7% compared to the emission from the engine assumed as operated without malfunctions. The engine operated with the exhaust gas duct throttling reduces total weighted emission CO (Fig. 2a) by 3% and the engine operated with throttling of the intake air duct increases the total weighted CO emission by 7% compared to the emission from the engine assumed as operated without malfunctions. According to results, presented in Fig. 2b, simulated malfunctions of the engine gas exchange system did not resulted in significant changes in total weighted emission $CO_2$ (change by 1%).

### 3.1. Throttling of the exhaust gas duct

As shown in Fig. 3a $NO_x$ emission decreases with an increasing of the engine load. The fuel combustion process-taking place in the environment of high temperature and high pressure. It is the main cause of $NO_x$ formation in the exhaust gas. The greatest reduction in $NO_x$ emission was achieved during engine operation at 60 kW loads. Observed reduction of $NO_x$ emission equals 13%. On the other hand, at the engine load ranges of 120 kW and 60 kW the CO emission reduces by 7-17 %. This result is shown in Fig. 3a and Fig. 3b. For other considered loads of the engine operation the emissions of $NO_x$ and CO has been reduced by 3-5% in relation to the engine operation without malfunctions. Throttling of the exhaust gas duct did not significantly affected the level of λ. Mentioned result is presented in Fig. 3d. The observed change of the λ value is approximately 2 %.

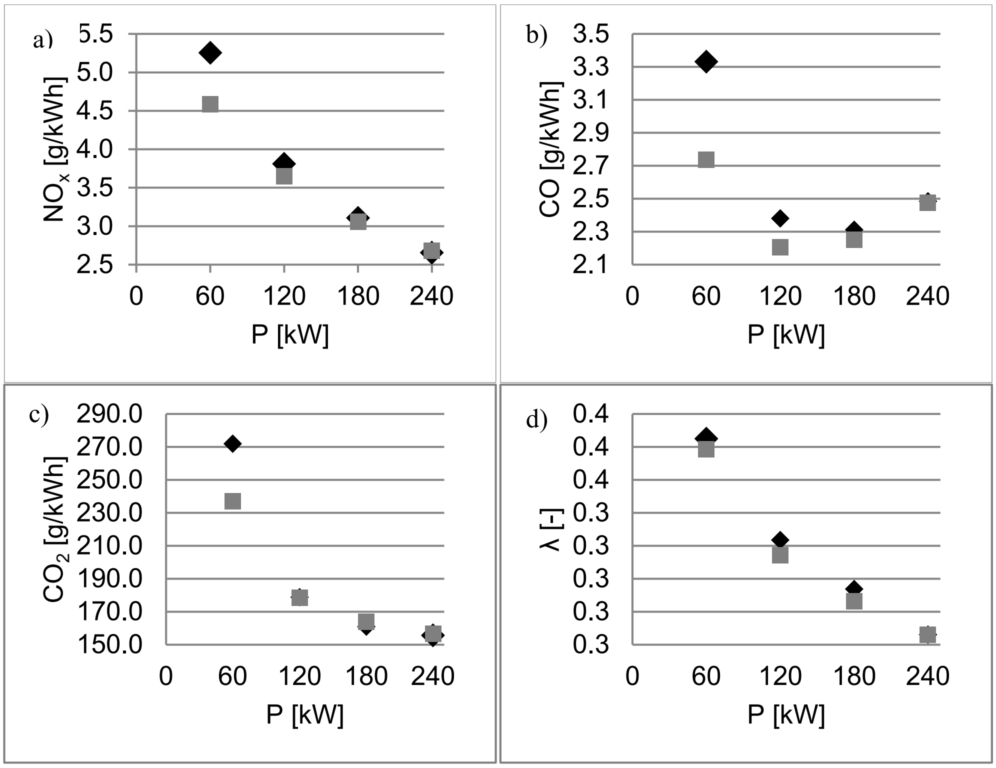


*Fig. 3. The results of the a) $NO_x$, b) CO, c) $CO_2$ emissions and d) λ for all considered loads and observations: ◆ − The engine assumed as operated without malfunctions, ■ − throttling of the exhaust gas duct*

Figure 3c presents the $CO_2$ emission for the operation of the engine with both without malfunctions and with simulated exhaust gas duct throttling. The change in $CO_2$ emission is affected by the change in the fuel consumption. The applied method of determining the specific fuel consumption in g/kWh consisted of measuring the time required to combust specified volume of fuel. Results of specific fuel consumption calculations are presented in Tab. 4. During all considered loads of the engine the best expected results were observed during engine operation at 60 kW load. At this load, the $CO_2$ emission has been reduced by 12% and specific fuel consumption by 13% in relation to the engine operation without malfunctions. In Tab. 4 the weighted average according to the cycle E2 (Tab. 3) of specific fuel consumption for the engine operating without malfunctions and simulated engine malfunctions were presented. According to the data presented in Tab. 4 total weighted engine's efficiency has been improved during engine operation with simulated throttle of the exhaust gas duct by 3%. The assumption of the measuring cycle E2 (Tab. 3) is that the engine operates with the 75% of the maximum load by 50% of overall operating time. The time measurement accuracy of specified volume of fuel combustion is estimated at 1.6% [4]. The differences are not significant which is within the range of measuring error of the used method.

### 3.2. Throttling of the intake air duct

Figure 4a shows the $NO_x$ emission during engine operation with simulated intake air duct throttling compared to the engine operation without malfunctions. Emission of $NO_x$ in exhaust gases from the marine diesel engine with simulated intake air throttling was decreased by 4-13% in

*Tab. 4. The specific fuel consumption in [g/kWh] [4]*

| | Power, P [kW] | The engine assumed as operated without malfunctions | Throttling of the exhaust gas duct | Throttling of the intake air duct |
|---|---|---|---|---|
| 1 | 240 | 277 | 279 | 285 |
| 2 | 180 | 286 | 289 | 292 |
| 3 | 120 | 315 | 311 | 318 |
| 4 | 60 | 477 | 413 | 418 |
| The weighted average of E2 test cycle | | 317 | 309 | 313 |

all considered loads of the engine. The largest decrease in $NO_x$ emission occurred during the marine diesel engine's operation load of 60 kW. The increase in the engine load increases the amount of fuel injected into the cylinders. The increasing of the injected amount of fuel is connected with the necessity to provide a greater amount of air to produce the correct fuel-air mixture in the combustion chamber of the marine diesel engine. The presence of CO in the exhaust gas is the result of a local or global deficiency of oxygen in the fuel combustion process in the combustion chamber of the marine diesel engine. Accordingly, there is a process of an incomplete combustion of carbon from the fuel. Relationship between the quantity of CO and $\lambda$ can be seen in Fig. 4b, d. CO emission significantly increased during the engine operation between 180 kW and 240 kW loads. Throttling of the intake air duct led to a reduction of $\lambda$ and therefore to a deterioration of the air-fuel mixture generated in the combustion chamber. The increase in CO emission in comparison to the engine without malfunctions was 10-12% and the reduction in $\lambda$ was 7-11% in the highest considered loads. CO emission in comparison to the engine without malfunctions decreased by 4-9% during the engine operation between 60 kW and 120 kW loads. The $\lambda$ value during the engine operation between 60 kW and 120 kW loads decreases by 1-12% as compared to the engine without malfunctions. $CO_2$ emission is presented in Fig. 4c. According to presented results of $CO_2$ emission decreases by 6-11% between 60 kW and 120 kW of the engine loads. The increase in $CO_2$ emission by 3-4% was observed between 180 kW and 240 kW of the engine loads. The increase in CO and $CO_2$ emissions from the engine with the simulated intake air duct throttling was linked with the change in the specific fuel consumption and therefore deterioration of the engine efficiency. The deterioration of the combustion process due to the intake air duct throttling led to the increase in the injected amount of fuel for combustion by 1-3% between 180 kW and 240 kW of the engine loads. It should be noted that the engines with classic camshaft are adjusted in order to achieve the best efficiency during operation with nominal load. Total weighted performance of the laboratory marine diesel engine with the simulated malfunction of throttling of the intake air duct according to the E2 cycle was improved by approximately 2% in comparison to the efficiency of the engine without malfunctions.

## 4. Conclusions

The article presents the results of the laboratory research of the four – stroke marine diesel engine, Sulzer 3 Al 25/30 type. Emissions of $NO_x$, CO, $CO_2$ and fuel consumption were measured according to the requirements of Annex VI to the MARPOL Convention. The E2 measurement cycle has been used. Measurements for simulated malfunctions of the engine air-exhaust gas exchange system were performed. Obtained results allow formulating the following conclusions:

- the examined simulated malfunctions cause changes in the total weighted emissions of $NO_x$, CO, $CO_2$. Changes in the total emission values ranged from 1 to 7 %. Simulated malfunctions during the marine diesel engine's operation with a considered load resulted slightly changes (by 2-3%) in the total weighted engine efficiency which are within the range of measuring error of the used method,

- simulated throttling of both the exhaust gas duct and intake air duct resulted in decreased fuel consumption by 13% and reduced emissions of the examined exhaust components by 4-17 % during engine operation at low loads. For other considered engine loads, changes in the examined emissions amounted to 3-5%,
- the simulated intake air duct throttling led to the increase in CO and $CO_2$ emissions compared to the engine without malfunctions by 3-12% and reduction of λ by 7-11% between the 180 kW and 240 kW of the engine loads. In the highest considered load of the marine diesel engine, the increase in specific fuel consumption by 1-3% was observed.

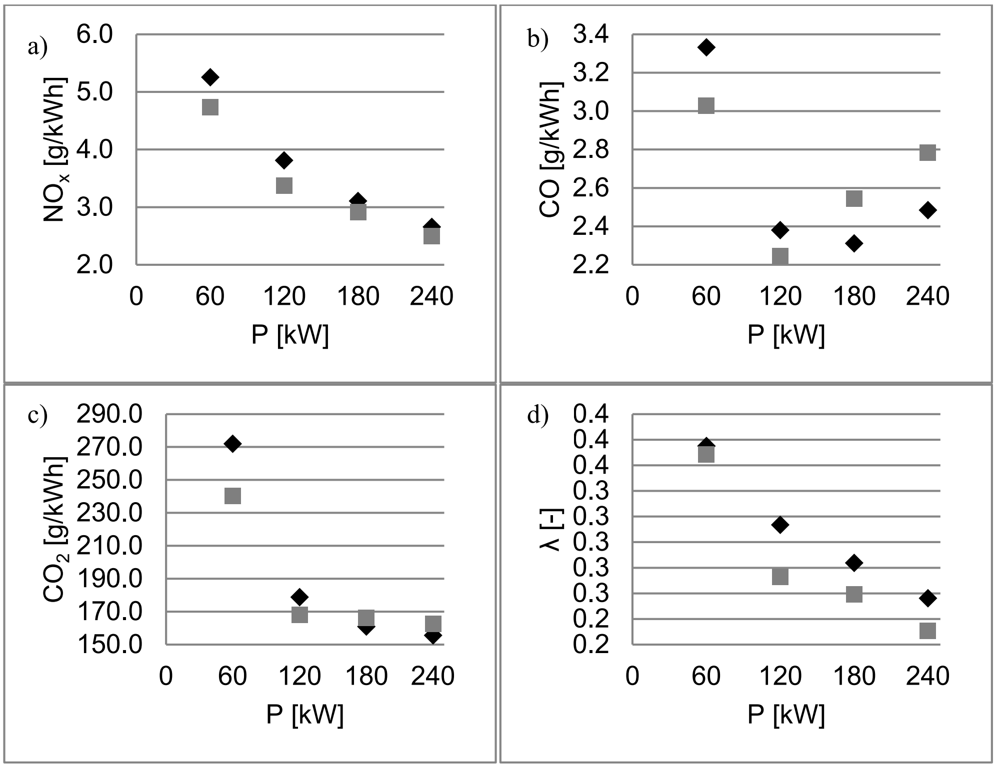


*Fig. 4. The results of the a) $NO_x$, b) CO, c) $CO_2$ emissions and d) λ for all considered loads and observations: ◆ − the engine assumed as operated without malfunctions, ■ − throttling of the intake air duct*


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**References**


[1] Charchalis, A., *Diagnostic and Measurement System Dedicated for Marine Engines Exploitatory Attributes Evaluation*, Journal of KONES, Vol. 19, No. 1, 2012.

[2] ISO 8178 Regulation, International Organization for Standardization.

[3] Jalkanen, J.-P., Brink, A., Kalli, J., Pettersson, H., Kukkonen, J., Stipa, T., *Modelling System for the Exhaust Emissions of Marine Traffic and its Application in the Baltic Sea Area*, Atmos. Chem. Phys., 9, 9209-9223, 2009.

[4] Lewińska, J., Kowalski, J., *Influence of the Marine 4 – stroke Diesel Engine Malfunctions on the Nitric Oxides Emission*, Journal of KONES Powertrain and Transport, European Society of Powertrain and Transport Publication, Warsaw 2013.

[5] Piotrowski, I., Witkowski, K., *Okrętowe Silniki Spalinowe*, Trademar, Gdynia 1996.

[6] *Revised Marpol Annex VI: Regulations for the Prevention of Air Pollution from Ships Resolution MEPC,* 176 (58), International Maritime Organization, 2008.
[7] Sarvi, A., Fogelholm, C.-J., Zevenhoven, R., *Emissions from Large-Scale Medium Speed Engines: 1. Influence of Engine Operation Mode and Turbocharger*, Fuel Processing Technology 89, 510-519, 2008.
[8] Sarvi, A., Fogelholm, C.-J., Zevenhoven, R., *Emissions from Large-Scale Medium Speed Engines: 2. Influence of Fuel Type and Operating Mode*, Fuel Processing Technology 89, 520-527, 2008.
[9] Sarvi, A., Fogelholm, C.-J., Zevenhoven, R., *Emissions from Large-Scale Medium Speed Engines:3. Influence of Direct Water Injection and Common Rail*, Fuel Processing Technology 90, 222-231, 2009.
[10] *Technical Code on Control Emission of Nitrogen Oxides form Marine Diesel Engines, Resolution* MEPC, 177 (58), International Maritime Organization, 2008.