THE DETECTION OF SELECTED MARINE ENGINE MALFUNCTIONS ON THE BASIS OF THE EXHAUST GAS COMPOSITION

Jerzy KOWALSKI

Gdynia Maritime University
Department of Engineering Sciences
Morska Street 81-87
81-225 Gdynia, Poland
tel.: +48 58 6901434, fax: +48 58 6901399
e-mail: jerzy95@am.gdynia.pl

Summary

Marine diesel engines are generators of mechanical energy, but also are generators of toxic compounds into the atmosphere. The composition of the exhaust gas may be a carrier of diagnostic information about the condition of functional systems of the engine. Results of the classification and selection of diagnostic signals for selected marine engine malfunctions are presented. The analysis was based on results of laboratory tests. Mentioned classification was able to isolate symptoms of malfunctions of marine 4-stroke diesel engine in the composition of the exhaust gas. Complementary detection signals are exhaust gas temperature behind each cylinder. The conclusion of this work is the ability to detect by this method such engine malfunctions as the throttling the air intake duct, the throttling of the exhaust gas duct, the decreasing and the increasing of fuel injection pressure on the selected cylinder, chocked or discalibrated fuel injector, the leakage of the fuel pump, changing of the fuel injection timing and exhaust and inlet valves malfunctions.

Keywords: marine engine, malfunctions detection, exhaust gas composition, data classification

WYKRYWANIE WYBRANYCH NIESPRAWNOŚCI SILNIKA OKRĘTOWEGO W OPARCIU O SKŁAD EMITOWANYCH SPALIN

Streszczenie

Silniki tłokowe generatorami energii mechanicznej, ale również generatorami emisji związków toksycznych do atmosfery. Skład emitowanych spalin może być nośnikiem informacji diagnostycznej o stanie technicznym układów funkcjonalnych silnika. W pracy przedstawiono wyniki klasyfikacji i wyboru sygnałów diagnostycznych dla wybranych niesprawności silnika okrętowego. Analiza została oparta na wynikach badań laboratoryjnych. W wyniku przeprowadzonych działań udało się wyodrębnić symptomy niesprawności 4-suwowego silnika okrętowego w składzie emitowanych spalin. Sygnałami uzupełniającymi detekcję są temperatury gazów spalinowych za poszczególnymi cylindrami. Wnioskiem z prezentowanej pracy jest możliwość wykrycia tą metodą takich niesprawności silnika jak dławienie kanału dolotowego powietrza i wylotowego spalin, obniżenie i zwiększenie ciśnienia wtrysku paliwa do wybranego cylindra, zakoksowanie lub rozkalibrowanie wtryskiwacza, przecieki w pompie paliwowej, zmiana rozpoczęcia wtrysku paliwa oraz wypalenie gniazd zaworów dolotowych i wylotowych.

Słowa kluczowe: silnik okrętowy, wykrywanie niesprawności, skład spalin, klasyfikacja danych

1. INTRODUCTION

Modern and properly marine engine with 10000kW of nominal power consumes about 48 tons of fuel and emits more than 3 tons of nitric oxides per day into the atmosphere. Abnormalities in the operation of marine piston engines cause an increase of fuel consumption and an increase of the emission of toxic combustion products into the atmosphere. The result is the deterioration in the economic conditions of maritime transport and the increase in the environmental pollution. For this reason, technical diagnostics of marine engines is an important problem in the operation of ships. The increase in the environmental pollution induced International Maritime Organization (IMO) for enacting provisions on the prevention of the pollution at sea [1]. These provisions impose on shipowners the necessity to control and reduce emissions of toxic compounds into the atmosphere. In addition, IMO encourages ship operators to continuously monitoring of toxic emissions. This approach increases the cost of the ship operation by the need to install the exhaust gas analyzer. On the other hand, monitoring of the composition of the exhaust gases can supply additional signals, enabled to increase certainty of the technical diagnosis of the marine engines. Usage of the exhaust gas composition analysis requires the identification of symptoms of marine diesel engine malfunctions. The preliminary research allow for the assumption that the composition of the exhaust gas contains diagnostic symptoms of selected engine failures in [2], [3].

The main purpose of this study is the identification of symptoms of selected marine engine malfunctions in the composition of the exhaust gas. For this purpose, laboratory studies on the marine engine piston were conducted. Mentioned research allows classify the qualitative relationship between the selected marine engine malfunctions and the composition of the exhaust gas.

2. LABORATORY RESEARCH

In order to identify symptoms of engine malfunctions in the composition of the exhaust gas laboratory tests on the 3AL25/30 engine were carried out. Parameters of the test engine are shown in Tab.1.

Table 1 Parameters of the laboratory engine

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	–
Injector nozzle		
Holes number	9	–
Holes diameter	0.325	mm
Opening pressure	25	MPa

Laboratory tests consisted of measuring operating parameters of the engine, along with the registration of the composition of the exhaust gas during the engine operation with following malfunctions:

– the throttling of the exhaust gas duct (dlawspal),
– the throttling of the air inlet duct (dlawpow),
– shift of the fuel pump cam on the camshaft, causing the delay of the fuel injection (katwtr),
– the leakage of the air inlet valve (dolot),
– the leakage of the exhaust gas valve (wylot),
– the decreasing of opening pressure of the fuel injector (wtr150),
– the increasing of opening pressure of the fuel injector (wtr350),
– the chocked fuel injector (zakoks),
– the discalibrated fuel injector (rozkalib),
– the leakage of the fuel injection pump (przeciek).

Designations of marine engine malfunctions are given in parentheses, appearing on figures. During the test engine operated at a constant speed, which corresponds to the marine engine operation to generators propulsion or the main engine operation with the fixed pith propeller [4].

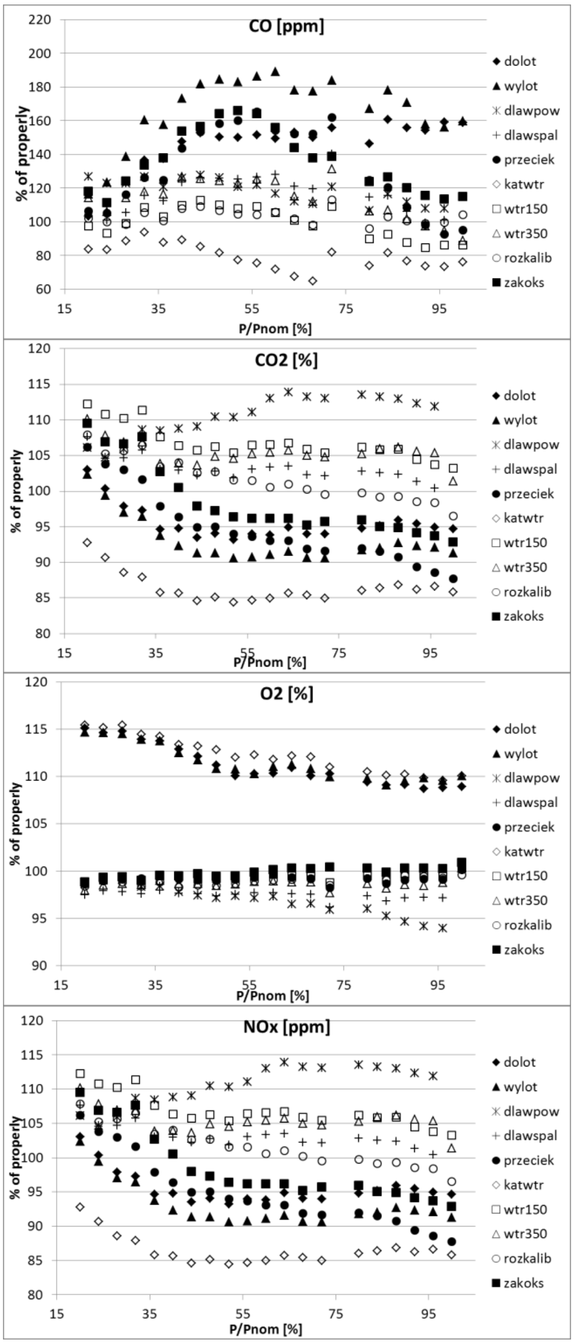

Fig.1 The exhaust gas composition

The test procedure, parameters of measuring devices and the analysis of results are presented, i.e. in [5], [6], [7].

3. RESULTS

During laboratory tests the exhaust gas composition and thermodynamic parameters of the engine needed to determine of emissions were measured. Fig.1 presents mean values for all observations of carbon monoxide (CO), carbon dioxide (CO_2), oxygen (O_2) and nitric oxides (NOx) fractions in the exhaust gas. Mentioned values are results of relative fractions in relation to the engine operation considered as properly for a range of engine load from 20% to 100% of the nominal load (Pnom).

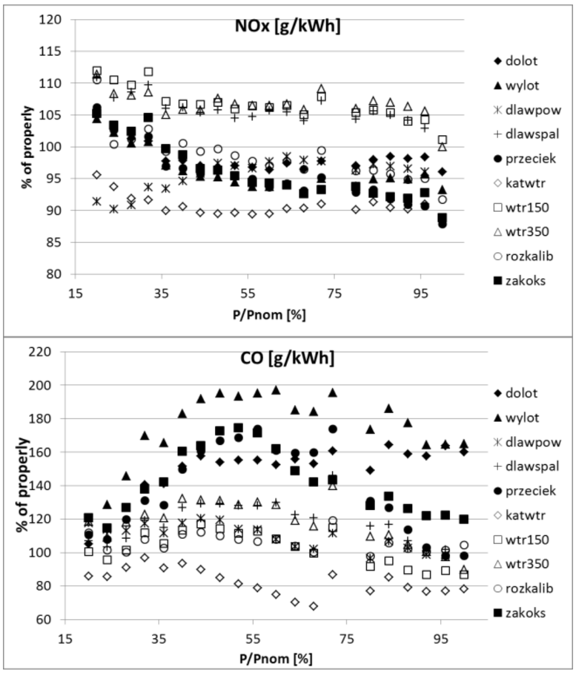

Fig.2 CO and NOx emissions

According to presented results, simulated engine malfunction cause a change in the organization of the combustion process in engine cylinders. The result is a change in fractions of chemical compounds in the exhaust gas. For example, the throttling of the exhaust gas duct, causes up to 80% increase of the CO fraction in the exhaust gas.

Introduced piston engine malfunction influences on combustible mixture, which leads to changes in the fuel brake-up, the vaporization, and changes time of autoignition [5], [8]. According to results presented on Fig.1, the change in the organization of the combustion process increases the CO fraction in the exhaust gas in the case of deterioration of the combustion process, an increase of the CO_2 fraction in the case of increased fuel consumption and the change in the NOx fraction caused by changed distribution of temperature and pressure in cylinders of the engine. Sulfur oxides fraction in the exhaust gas largely depends on the sulfur content in fuel and therefore are omitted in resented considerations. Among presented results, the O_2 fraction in the exhaust gas explicitly changes only at the engine operation with the throttled air inlet duct or the throttled exhaust gas duct. Other engine failures did not cause significant changes in O_2 fractions. For this reason, this parameter is excluded as a carrier of engine failure symptoms. Please note that emission characteristics of piston engines are not identical, because depend on the individual design and the engine management control. Important is the fact that the composition of the exhaust gas carries diagnostic symptoms of simulated malfunctions.

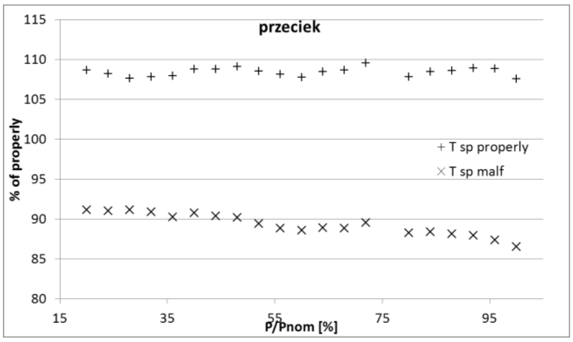

Fig.3 Exhaust gas temperature behind the cylinder recognized as properly (Tsp properly) and behind the cylinder with the leakage of the fuel injection pump (Tsp malf)

It should be noted that fractions of chemical compounds in the exhaust gas are not complete information about toxic emissions. The standard adopted control parameter is the emission presented in g/kWh or similar. Unfortunately, the measurement of emissions associated with the measurement of additional parameters of the engine, which allows quantifying of chemicals emissions into the atmosphere. [9]. These parameters are primarily the exhaust gas flow rate, which is very troublesome to measure and obtained results are often burdened by significant errors. The determination of the exhaust gas flow rate is also possible by the measuring of fuel consumption and the air flow rate, but in the case of large marine engines the air flow rate measurement can also be exposed to considerable measurement error. There is also, allowed by the standard [9], the method of the carbon balance, which allows the calculation of the exhaust gas flow rate based on the measurement of fuel consumption and the exhaust gas chemical analysis. Please also note that the NOx fraction and the NOx emission depend on the humidity, temperature and pressure of the engine surrounded air. For this reason, it would be appropriate to use, as the source of diagnostic signals, emission characteristics of the engine. On the Fig.2 the NOx emission, corrected to the standard conditions [9] and the CO emission are presented. Presented values are mean values of all observations.

According to presented results, emission characteristics of the marine engine contain information about simulated engine malfunctions also. The comparison of results from Fig.1 and Fig.2 shows that changes in emissions for the considered engine malfunctions are 2% to 6% higher in comparison to observed changes of gaseous components fractions in the exhaust gas.

4. CLASSIFICATION

Considered engine malfunctions can be classified into two categories:

- malfunctions of the air/exhaust gas exchange system,
- malfunctions located in engine cylinders.

In the case of second category of engine malfunctions the detection of the type and the size of malfunctions is required, and the identification of faulty cylinder is required also.

use symptoms included in components fractions in the exhaust gas. The analysis of results allows the qualitative identification of the engine malfunction based on the set of diagnostic information carriers. As is apparent in Tab.1, presented results were collected for the 3 cylinder engine. It should be assumed that in the case of the malfunction occurring in one cylinder of a larger number of engine cylinders, the response of diagnostic symptoms may not be so clear. Therefore, it was assumed that the information carrier is the only signal which value is changed by more than 5% in relation to the signal coming from the engine considered as properly. Moreover, all observations from laboratory tests were analyzed.

Tab.2 Qualitatively classification

Malfunction	CO_2 [%]	CO [ppm]	NOx [ppm]	Tsp malf	Tspal properly
dlawspal	–	↑*	–	↑	↑
dlawpow	↑	↑	↑	↑**	↑**
katwtr	↓	↓	↓	↑*	–
dolot	↓**	↑	–	↑*	–
wylot	↑*↓**	↑	↓	↑**	–
wtr150	↑*	↑*↓**	↑	–	↑
wtr350	–	↑*	↑	–	↑*
zakoks	↑*	↑	↑*↓**	↓*	↑*
rozkalib	↑*	–	↑*	↑	–
przeciek	↓**	↑*	↓	↓	↑

* - low load, **-high load

For this reason, a set of parameters, identifying the malfunction of the engine should be extended with a parameter derived from individual cylinders. Accessible and easy to measure parameter is temperature of the exhaust gas behind engine cylinders. Fig.3 presents exemplary results for the engine operation with the leakage of the fuel injection pump on one of engine cylinders (przeciek). According to presented results for the exhaust gas temperature behind the cylinder with the leakage of the fuel injection pump (Tsp malf) is about 10% lower and exhaust gas temperature behind other cylinders (Tsp properly) is about 7% higher for all considered engine loads in relation to exhaust gas temperature behind cylinders of the engine considered as properly. It should be noted that presented values are dependent on the intensity of the malfunction and the number of engine cylinders.

The analysis allows to the selection of diagnostic symptoms carriers of selected marine engine malfunctions. Due to the direct method of measurement the following set of signals was chosen; the NOx fraction corrected to standard conditions [9], CO and CO_2 fractions in the exhaust gas of the engine and exhaust gas temperature behind each cylinder. Despite the fact that the CO and the NOx emission includes diagnostic symptoms of the engine malfunction also, due to the complexity of the carbon balance method, hindering the application at the sea condition, it was decided to

Tab. 2 presents results of qualitatively classification of considered signals. The mark (↑) means the increase of the fraction or temperature and the mark (↓) means the decrease of the fraction or temperature in relation to the signal coming from the engine considered as properly. According to presented results, each of considered malfunctions can be identified by using the presented set of the data.

The engine exhaust valve leakage was simulated by drilling in the popped valve head 4 holes with a diameter of 2 mm each. The diameter of the valve head equals to 98mm. Experimental results show that even such large malfunction does not cause any significant changes in temperature of the exhaust gas behind cylinder. This malfunction causes a significant change in the CO and the NOx fractions. Moreover, none of the simulated engine malfunctions did not cause activity of the alarm, informing about exceeding the limit values of measured thermodynamic parameters. Mentioned information allows the conclusion that the presented detection method can in some cases be more sensitive than standard accepted methods of diagnosis used in marine engine operations. It should be noted, that the data presented in Tab.2 are true only for the type of the engine presented in Tab.1.

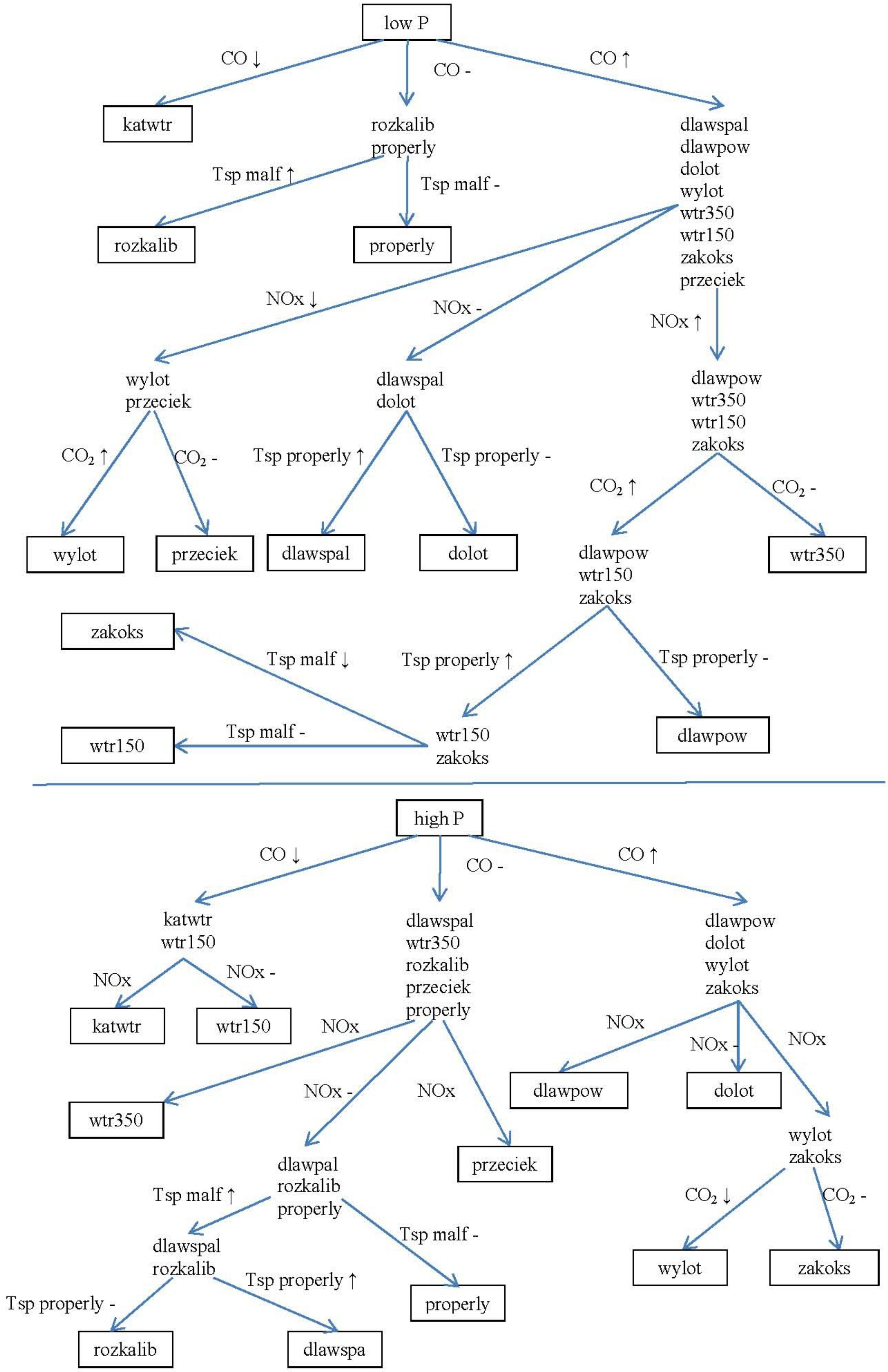

Fig.4. Classification trees

Settings changing of the engine or the size change of the engine malfunction could result in a different diagnostic answer.

The data collected in Tab.2 allow using one of the methods of data mining. Mentioned methods allow classifying the considered malfunction with selected carriers of diagnostic signals. The simplest and at effective solution is a classification tree [10]. According to results contained in Tab.2 the part of diagnostic symptoms are visible only at low the engine load operation and some at high the engine load operation. Thus it's necessary preparing two classification trees for low and high the engine load conditions.

Fig.4 presents the classification tree for low and high the engine loads using the considered set of signals. Branches of the tree define the test logic and rectangular frames show the result of the malfunction classification, marked as described in Tab.2. According to presented results considered set of signals in the form of the NOx, the CO and the CO_2 fractions and exhaust gas temperature behind cylinders allows the classification of the malfunction by up to 5 logical tests for the engine operation at the low load condition. Classification tree, prepared for high engine loads allows for classification of considered malfunctions using up to 4 logical tests. It should be noted that the presented data is true only for marine engine parameters consistent with Tab.1. Mentioned classification tree is not the diagnostic system. Considered classification trees are evidence of the ability to detect considered marine engine malfunctions with signals coming from the composition of the exhaust gas.

5. CONCLUSIONS

The present work aimed to identify symptoms of selected marine engine malfunctions in the composition of the exhaust gas. For this purpose, laboratory studies on the marine piston engine were conducted. Obtained results allow us to classify the qualitative relationship between selected marine piston engine malfunctions and the composition of the exhaust gas. On the basis of the presented logical analysis, following carriers of diagnostic signals were isolated: the carbon monoxide and the carbon dioxide fractions in the exhaust gas, the nitric oxides fraction corrected to standard conditions, and exhaust gas temperatures behind each marine engine cylinder. The classification of symptoms obtained with the diagnostic classification tree was carried out also.

The carried out work permits to identify diagnostic signals of considered marine engine malfunctions in the composition of the exhaust gas.

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Jerzy KOWALSKI is a researcher in Department of Engineering Sciences at Gdynia Maritime University-Poland. He obtained a Ph.D. in 2006, at Gdynia Maritime University, with a thesis on combustion and pollutants modeling in 2-stroke marine engines. He is the head of an research team, dealing with possibility of the technical diagnosis of marine engines during onboard operation.