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Diagnosis of marine internal combustion engines by means of rapidly variable temperature and composition of exhaust gas as an alternative or support for currently used diagnostic methods

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The article points out the relevance of parametric diagnostics of ship engines and analyzes the state of research in this field. A method is proposed for diagnosing engine systems on the basis of rapidly variable exhaust temperature while measuring its composition. A method for determining diagnoser tools from the signal within one engine cycle and mathematical and statistical treatment of test results is presented. The products of numerical modeling in the Diesel-RK software and the products of laboratory research on a Farymann Diesel test engine were analyzed. The effect of the most popular defects on the analyzed parameters was defined. Criteria for matching a diagnoser tool in accordance with the type of damage in a ship engine were presented. A methodology was proposed for adapting the presented method to metering on a ship engine in operation.

Key words: *ship IC engine, exhaust gas temperature, diagnostic informativeness, F-statistic of Fisher-Snedecor distribution, environmental impact of exhaust gas*

1. Introduction

1.1. State of knowledge in the analyzed area

Degradation phenomena: tribological, erosion, and corrosion result in the gradual destruction of the engine's structural structure and consequently in states of operational unfitness [24]. The existing states of unfitness or partial loss of fitness of internal combustion engine systems are associated with a series of consequences. The following aspects are considered here:

– technical (i.e., lower engine performance)
– economic (i.e., higher consumption of fuel and oil)
– ecological (i.e., increased emissions of pollutants contained in exhaust gases and operating fluids)
– safety (i.e., greater risk of breakdown, loss of propulsion)
– legal (i.e., penalties for raised emissions, disqualifications).

For several years, based on international regulations, efforts have been made to effectively reduce atmospheric emissions of toxic compounds contained mainly in the combustion products of marine and land-based internal combustion engines and other fuel-fired equipment. The primary regulation for the prevention of air pollution from ships is Annex VI to MARPOL 73/78, and the rules contained therein deal with restrictions on emissions of environmentally harmful substances, which include nitrogen oxides (NO_x), sulfur oxides (SO_x), particulate matter (PM), ozone-depleting substances (halons, freons) and volatile organic compounds (VOCs) [7, 11, 48]. For automobiles in Europe, there are two main pieces of legislation limiting emissions: Euro 6 and Euro VI. Regulation No. 715/2007 is a type-approval standard for light passenger cars and vans with regard to emissions and access to vehicle repair and maintenance information (Euro 5 and Euro 6). Heavy-duty vehicle emissions (Euro 6) sets the rules for the type-approval of motor vehicles, engines, and spare parts for heavy-duty vehicles with regard to their emissions [39, 40].

A very big environmental problem today is the emission of toxic gases in the exhaust of marine engines powered by low-quality fuels. For example, just one in eight of the world's largest container ships is responsible for emitting the same amount of contaminants into the atmosphere (annually) as 50 million cars [25].

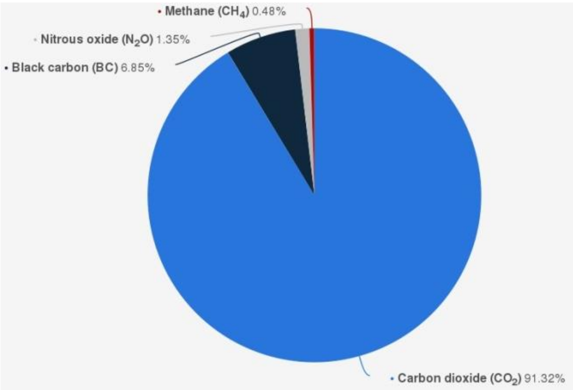


Fig. 1. Distribution of greenhouse gas emissions produced by the global shipping industry in 2018 by emission type [13]

Ship engines are a key source of pollution, mainly due to the high carbon dioxide content of the exhaust (Fig. 1 and Fig. 2), which contributes to the greenhouse effect but also due to emissions of nitrogen oxides and sulfur oxides [32]. CO_2 emissions from ships continue to show an upward trend (Fig. 2), while in recent years, more attention has been paid to reducing emissions of this compound from automotive (land-based) sources. The issue of sulfur pollution relates to engines running on residual fuel but has been partially reduced thanks to the mentioned regulations, as can be seen in Fig. 3.

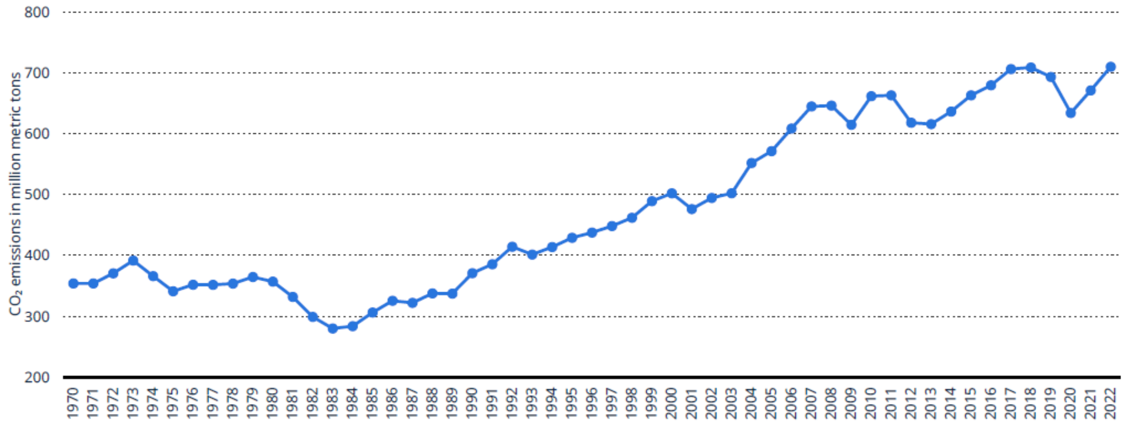


Fig. 2. Carbon dioxide emissions as a function of the year from international shipping from 1970 to 2022 [13]

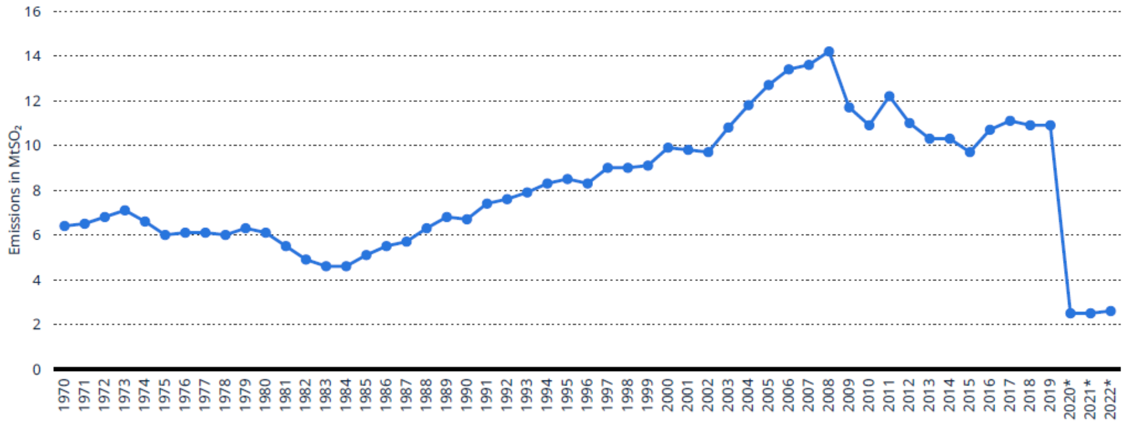


Fig. 3. Sulfur dioxide emissions as a function of the year from international shipping worldwide from 1970 to 2022 [13]

a) b) c)

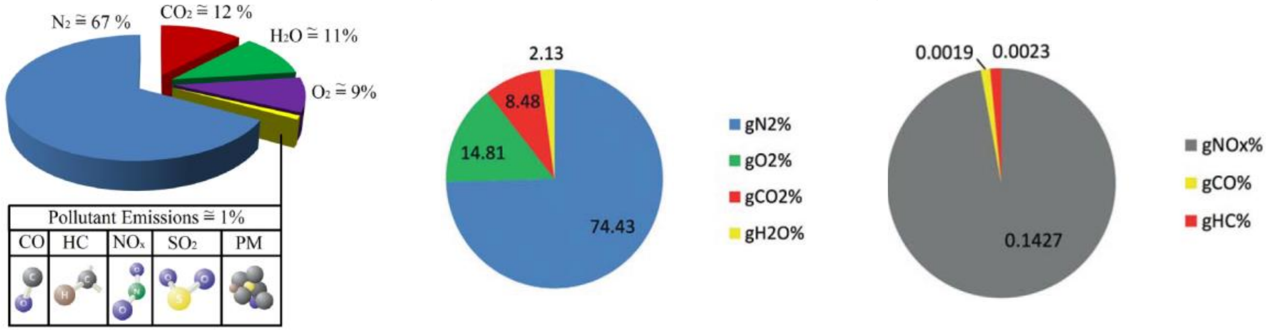


Fig. 4. Composition of exhaust gas from a diesel-powered car engine (a) [41]; gaseous chemical composition of the exhaust of the ship engine powered by RMD 80 marine fuel: mass fractions of basic (N_2, O_2, H_2O) and harmful (CO_2) chemical compounds (b); mass fractions of toxic compounds (NO_x, CO, HC) (c) [25]

As many studies have shown, both exhaust from diesel-powered automotive engines (Fig. 4a) and exhaust from marine engines fueled with RMD residual fuel (Fig. 4b and Fig. 4c) contain a significant amount of harmful and toxic compounds. They are not inert to human and animal health and the environment [15, 25, 41].

The map of concentrations of harmful compounds in different load states during tests of the Sulzer 6AL20/24 engine was transferred to the computer program described in the article [1]. Thus, a mathematical model of the propulsion system and a computer program were created based on in-service measurements, which undoubtedly increases the diagnostic value and trustworthiness of the program [22, 51]. As can be seen in Figure 5, among other things, the authors created a map of NOx emissions depending on engine load and crankshaft speed. It can be seen that NO_x concentrations are highest at higher speeds and at an engine load of about 60%.

The research paper [9] presents an analysis of the impact of fuel supply system defects on the emission of toxic components of gasoline engine exhaust gas. In light of today's increasingly restrictive regulations and the safety and reliability of internal combustion engines, this is a very valuable work [9, 33]. As can be seen in Fig. 6 and Fig. 7, the authors measured with an exhaust gas analyzer the content of, for example, CO_2 for different technical states of the fuel supply system and as a function of rotational speed. You can see, for example, the increase in CO_2 when one of the injectors or lambda probe is disconnected.

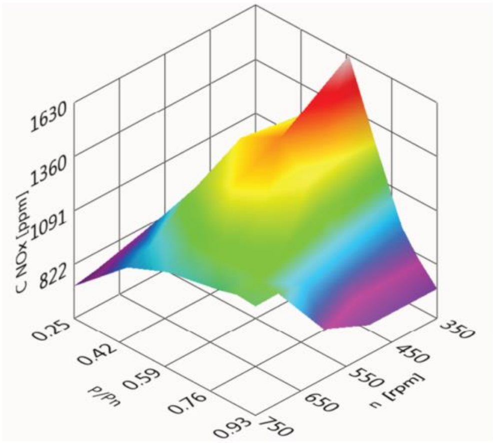


Fig. 5. Concentration NO_x map [1]

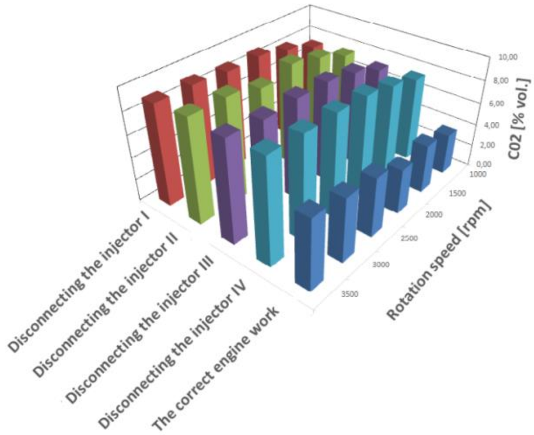


Fig. 6. Carbon dioxide content in the exhaust gas of a BMW engine fueled with petrol and in without ignition in individual cylinders [9]

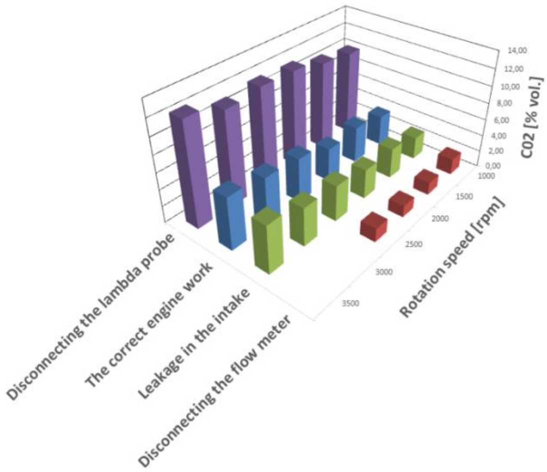


Fig. 7. The carbon dioxide content in the exhaust gas of a BMW engine fueled with petrol working efficiently and for simulated damage [9]

At the same time, technical and economic aspects should be kept in mind. As laboratory tests show, damage to the fuel supply system affects the pressure of the working medium in the inner chamber (and thus the performance and performance of the engine) – Fig. 8a. As the author points out, this is also associated with a negative effect of the condition of the injectors on the emission of harmful compounds in the exhaust gas. The same tests on the AL25/30 Cegielski-Sulzer marine internal combustion engine indicate a significant effect of injector damage on fuel consumption – Fig. 8b. An increase in specific fuel consumption of several percent (and even a dozen percent at lower loads) for marine engines is associated with a huge increase in operating costs [27].

In parallel with experimental research conducted on in-service engines [25] and research on laboratory engines [27], researchers are conducting simulation studies to improve methods for diagnosing internal combustion engines, including marine engines. As shown in simulation studies of a four-stroke marine engine, fuel supply defects affect changes in the temperature of the working medium (Fig. 9a), as well as NO_x emissions (Fig. 9b) [38]. Both T_{exh} and NO_x increases have a negative impact on most aspects of internal combustion engine operation, including economics and ecology.

a)

b)

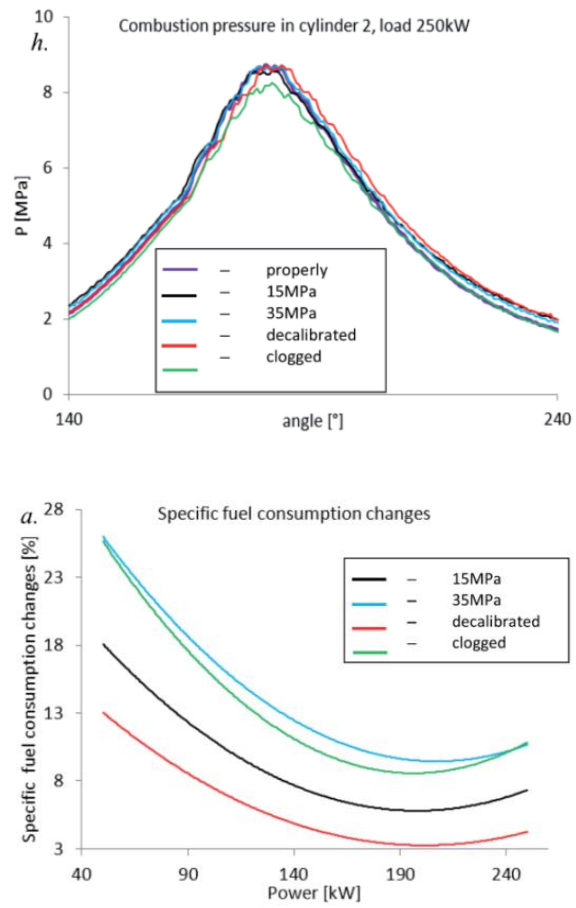


Fig. 8. Changes of combustion pressure of gas mixture in engine cylinder (a) and specific fuel consumption (b) for the experimental study consists of 5 stages, at different simulated malfunctions of the fuel injector installed in 2nd cylinder of the ship engine, where properly opening pressure is 25 MPa [27]

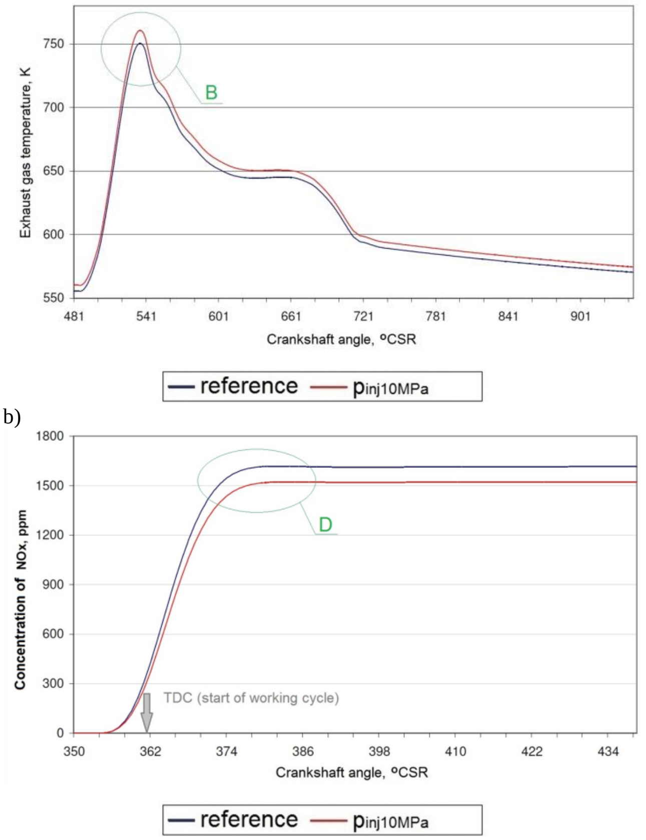


Fig. 9. Patterns of trends in: temperature of exhaust gas T_{exh}, for part of engine cycle and with marked highest incidence of the highest amount of the difference of temperature B (a); and concentration of NO_x particles and with marked highest appearance of the highest amount of the difference of concentration of NO_x particles D (b), derived as a product of numerical modeling of working process of engine regarding the introduced modifications in opening pressure of injector p_{inj} [38]

A very interesting computational model of thermodynamic processes in a cylinder was presented by scientists from Ukraine [20]. The authors found it effective for in-operation engine diagnostics. As can be seen in Fig. 10, they analyzed the effect of various types of damage on in-cylinder pressure. First of all, they analyzed mechanical and wear damage, which is quite common in both marine engines and vehicles (cylinder scratch, piston burnout, valve-seat gap, valve crack). The effect of almost all the analyzed damages on the pressure value is evident – in extreme cases, there is almost a cessation of the compression process. Simulation programs are an extremely important part of engine diagnostics because of the economical and less time-consuming and safe analysis of the impact of damage on the economy and ecology [4, 12, 14, 20, 23, 30].

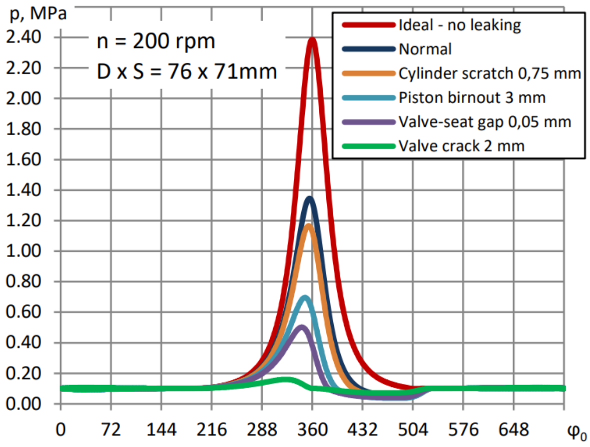


Fig. 10. The influence of various types of damage on compression obtained by modeling [20]

Table 1. Emissions with the new nozzles [A] and with nozzles with 9000 h of operation with limited opening pressure [B] for research of ship IC engine [8]

Loading six cylinders, 956 kW at 850 rpm	100%	75%	50%	25%
Measurements of NO_x – test cycle E2				
NO_x (ppm) [A]	1090	1033	977	764
Fuel (kg/h) [A]	181	137	96.7	54.2
NO_x (g/kW h) [A]	10.82	11.51	12.35	16.41
Measurements of NO_x – test cycle E3				
NO_x (ppm) [A]	1090	1182	1295	1620
Fuel (kg/h) [A]	182.1	137.7	97.2	55,3
Brake specific NO_x (g/kW h) [A]	10.82	11.32	12.31	16.87
Measurements of CO – E2				
CO (g/h) [A]	426	109	99	175
Fuel specific (g CO/kg fuel) [A]	2.35	0.79	1.02	3.22
Measurements of CO – E3				
CO (g/h) [A]	426	329	335	116

Loading six cylinders, 956 kW at 850 rpm	100%	75%	50%	25%
Measurements of NO_x – E2				
NO_x (ppm) [B]	973	943	824	630
Fuel (kg/h) [B]	182.3	137.8	97.1	54.9
NO_x (g/kW h) [B]	10.16	10.82	10.31	11.44
Measurements of NO_x – E3				
NO_x (ppm) [B]	973	1026	1135	1398
Fuel (kg/h) [B]	183.3	138.6	98	56.1
Brake specific NO_x (g/kW h) [B]	10.16	10.56	11.39	14.1
Measurements of CO – trial E2				
CO (g/h) [B]	945	378	207	184
Fuel specific (g CO /kg fuel) [B]	5.18	2.74	2.13	3.35
Measurements of CO – E3				
CO (g/h) [B]	945	804	759	214
Fuel specific (g CO/kg fuel) [B]	5.15	5.8	7.74	3.81

It is also diagnostically valuable to assess the effect of the condition of marine engine systems on emissions as a function of engine load. The study shows how injector nozzle wear affects emissions for the highest and operating engine loads – Table 1 [8]. The authors show a slight increase in NO_x [g/kWh] for both the highest (100%) and operating (75%) engine loads for a worn injector. However, in the case of CO [g/kg fuel], the increase is crucial (even more than 3 times), which, of course, is not insignificant for the environment.

Currently, the parameters measured on ships are recorded routinely due to ship safety and classification societies' requirements [16–18]. However, they are not sufficient for full diagnostics, and it is not always possible to diagnose the engine unambiguously. The diagnostic systems used can be aided by new diagnostic techniques [24]. It is not always possible to measure exhaust gas pressure while average temperature is measured. There is an information gap in rapidly variable measurements of exhaust gas temperature, which the author of this article considers possible valuable support for existing measurement systems without intervention in them [46, 47].

1.2. Purpose and placement of conducted research

The diagnostic methods currently used for marine engines are mainly based on vibroacoustic, endoscopic methods, analysis of engine exhaust gas parameters and components, and indicator chart analysis. In the absence of engine indicator capability, evaluation of engine condition by means of rapidly variable exhaust gas temperature fills the gap in parametric diagnostics.

Analysis of exhaust gas components for diagnostic purposes is now very well developed, as are the methods mentioned above. The author of this article proposes that the new diagnostic method on the basis of rapidly variable exhaust gas temperature should be supported by exhaust gas composition measurements and analysis (if possible) in order to exploit the potential of both methods.

Against the backdrop of the new requirements for emissions of harmful and toxic components of exhaust gases, the proposed duo seems to be very appropriate. Indeed, it is possible to simultaneously diagnose engine inoperability conditions while monitoring emissions. It should also be borne in mind that a single symptom does not give full information about the problem, and when two or more symptoms are known, we are closer to a proper diagnosis. Then, every technical, economic, legal, and environmental aspect is taken into account, and safety is ensured.

2. Proposed new method of diagnosing damage to a ship engine according to rapidly variable exhaust temperature

2.1. Test stand and measuring equipment

The research was carried out on the laboratory bench of a Farymann Diesel ship engine – Fig. 11 (P_{nom} = 6 kW, n_{nom} = 1500 min^{-1}, M_{nom} = 38 Nm, d_{cyl} = 90 mm, S_{cyl} = 120 mm, ε = 22:1, displacement 765 cm^3) [37].

The exhaust gas temperature t_{exh} was recorded with a K-type thermocouple, with an outer diameter of 0.5 mm. Exhaust gas pressure p_{exh} was recorded with an Optrand C12296 optical pressure sensor with a range of 0–100 psi and a vulnerability of $6.01 \cdot 10^{-8}$ V/Pa – Fig. 12. A multifunction module of the DT-9805 was used to record t_{exh} and p_{exh}, as well as the TDC signal [10, 29]. While the test, a n = 1444 rpm was kept, for engine loads of respectively P_1 = 432 W, P_2 = 768 W, P_3 = 1200 W. Throughout research, MGO type marine fuel was used. A KIGAZ-310 analyzer was used to monitor the composition of the exhaust gas in the outlet duct [21].

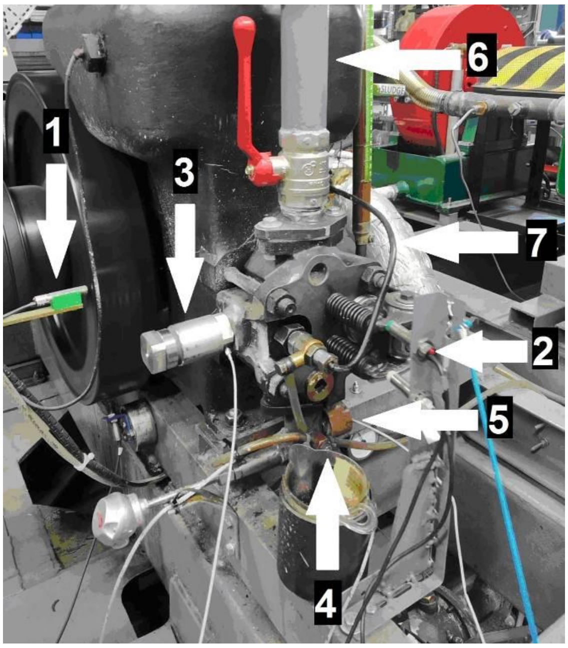


Fig. 11. View of the laboratory bench with the sensors of the recorded parameters marked: 1 – TDC and rotational speed sensor, 2 – exhaust outlet valve opening sensor, 3 – structural element regulating the volume of the combustion chamber together with the pressure sensor of the medium inside the combustion chamber, 4 – water-cooled thermocouple, 5 – duct pressure sensor, 6 – intake air (duct with control valve), 7 – fuel supply

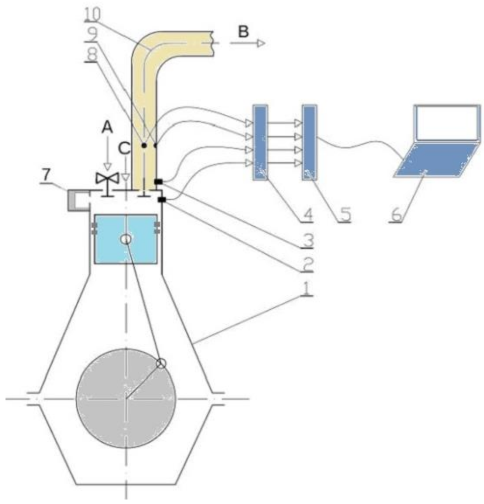


Fig. 12. Schematic of the laboratory bench with the mounting locations of the measurement sensors marked: 1 – test engine, 2 – TDC piston position and crankshaft rotational speed sensor, 3 – exhaust valve opening sensor, 4 – A/C converter, 5 – recorder, 6 – analysis software, 7 – structural element enlarging the volume of the combustion chamber, 8 – exhaust gas pressure sensor, 9 – thermocouple for rapidly variable measurements, 10 – exhaust gas channel, A – intake air, B – exhaust gas, C – supply fuel

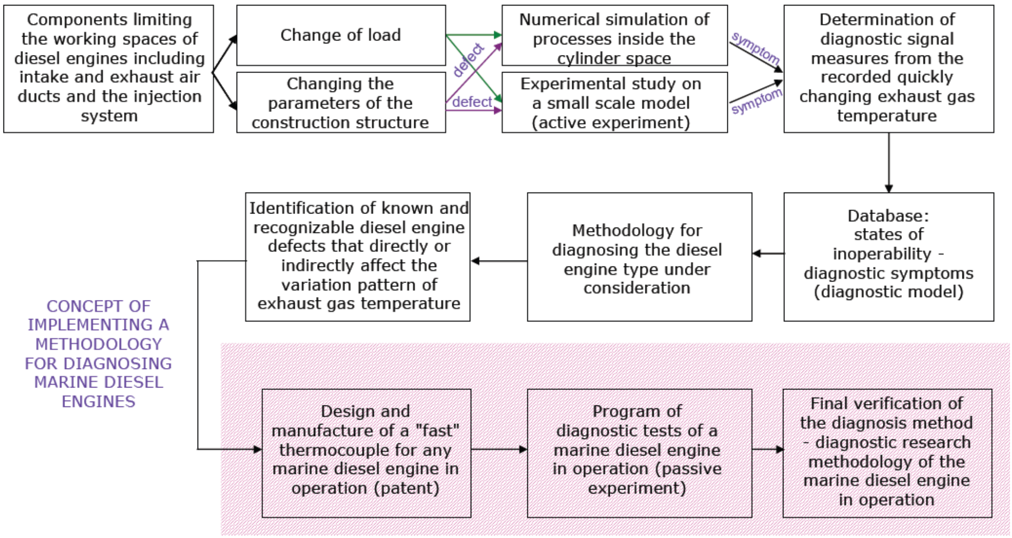


Fig. 13. Diagram of the realization of research of heat-flow processes in the exhaust gas duct for diagnostics of selected parts of systems of a ship engine

The input variables were the following parameters of the structure:

1. The active cross-sectional area of the inlet channel A_{in}, which decreased in amount by 50% compared to the reference condition.
2. The opening pressure of the fuel injector p_{inj} controlled by loosening the spring in the injector. The value was reduced from 12 MPa to 10 MPa.
3. The volume of the combustion chamber was changed, which was expressed in the value of the engine compression ratio ε. The reference value for the tested engine was 22:1, while the reduced value was 21:1. The reduction in the compression ratio was realized by using a part that increases the combustion chamber volume.

2.2. Description of the research method and mathematical analysis

The proposed research analyzed the thermodynamic processes taking place in the working spaces of a marine internal combustion engine, which was considered as a source of a rapidly varying exhaust gas temperature signal. An analogous analysis of the signal from other internal combustion engines is therefore possible. The proposed methodology for diagnosing marine engines should follow the steps shown in Fig. 13.

In proceeding to develop the plan for the active experiment, a literature analysis of the most common defects in marine internal combustion engine systems in service and the impact of these defects on engine performance was carried out [2, 42, 45, 48, 49]. In addition, numerical modeling of the operation process of a laboratory internal combustion engine was carried out for the same purpose. Diesel-RK software was used for numerical modeling of thermodynamic processes occurring in a reciprocating engine [6, 28, 34, 49]. During the numerical modeling of the processes, the compounds of the MGO-type feed fuel used during the experimental testing of this engine were introduced. According to the literature analysis and numerical modeling, it was considered that 3 engine systems would be analyzed during the experimental tests: fuel supply and intake air, as well as the combustion chamber, as the most critical systems elements.

The results obtained from the measurements were subjected to appropriate mathematical and statistical processing, according to the following steps:

1) interference from the recorded signal was removed from the measurement network
2) the real temperature of the exhaust gas was determined, taking into account the amplitude-phase shift [37]
3) diagnostic tools averaged over one engine cycle were defined: peak-to-peak value ΔT_{av}, specific enthalpy h and the strength of temperature trends $\Delta T/\Delta\tau\uparrow$
4) using the randomized complete plan, irrelevant input quantities were removed and eliminated from further diagnostic analysis [35]
5) a block randomized plan was implemented and a statistical analysis of the significance of the effect of structural data on the diagnostic tools was conducted against the background of changing loading conditions.

The specific enthalpy h is the result of integrating the temperature waveform calculated according to formula (1) below. Meanwhile, the strength of the temperature trend $\Delta T/\Delta\tau\uparrow$ defines the temperature increase over time (K/s) (2). For a real sinusoidal waveform, the values of $\Delta T/\Delta\tau$ for the rising and falling slopes are the same. The average peak-to-peak value ΔT_{av} is defined as the difference between the highest and lowest flue gas temperatures (3).

$$h = \int_0^{720} c_{pexh}(t_{exh}) \cdot t_{exh} d\alpha_{CSR} \text{ , J/kg} \tag{1}$$

where: h – specific enthalpy of the exhaust gas stream, the average over one engine cycle, J/kg, c_{pexh} (t_{exh}) – average specific heat of the exhaust gas at constant pressure, kJ/kg·°C, t_{exh} – exhaust gas temperature recorded over one engine cycle, °C, α_{CSR} – value of the engine crankshaft rotation angle, °CSR.

$$\left(\frac{\Delta t}{\Delta\tau}\uparrow\right)_{av} = \frac{t_{max} - t_{min}}{\tau(t_{max}) - \tau(t_{min})} = \left(\frac{\Delta T}{\Delta\tau}\uparrow\right)_{av} \text{ , K/s} \tag{2}$$

where: $(\Delta T/\Delta\tau\uparrow)_{av}$ – strength of the temperature trend, K/s, t_{max} – maximum exhaust temperature value over one engine operating cycle, ^{o}C, t_{min} – minimum exhaust temperature value over one engine operating cycle, ^{o}C, $\tau(t_{max})$ – time at which the exhaust gas temperature reaches the maximum value within one engine operating cycle, s, $\tau(t_{min})$ – time at which the exhaust gas temperature reaches the minimum value within one engine operating cycle, s.

$$\Delta t_{av} = t_{exhmax} - t_{exhmin} = \Delta T_{av}, \mathrm{K} \tag{3}$$

where: ΔT_{av} – average peak-to-peak value, K, $t_{exh\ max}$ – maximum temperature of exhaust gas within one engine operating cycle, ^{o}C, $t_{exh\ min}$ – minimum temperature of exhaust gas within one engine operating cycle, ^{o}C.

In the case of univariate analysis, it is possible to assess the significance of the effect of the input indicator considered in the diagnostic tests of an engine – it is a set of structural data within a certain range of variability on the diagnostic parameter (output indicator) defined in these tests.

In the case of assessing the effect of, for example, the opening pressure of the fuel injector on $\Delta T/\Delta\tau\uparrow$, a relationship is used that allows the calculation of the test statistic F_{cal} of the Fisher-Snedecor distribution and is compared with the critical value F_{cr} (tabulated). It is defined on the basis of the following relation[1]:

$$F_{cal} = \frac{\sum_{i=1}^{p} n_i \cdot (\overline{\Delta T/\Delta\tau_i} - \overline{\Delta T/\Delta\tau})^2 \cdot (n-p)}{\left[\sum_{i=1}^{p}\sum_{j=1}^{q} (\Delta T/\Delta\tau_{ij} - \overline{\Delta T/\Delta\tau})^2 - \sum_{i=1}^{p} n_i \cdot (\overline{\Delta T/\Delta\tau_i} - \overline{\Delta T/\Delta\tau})^2\right] \cdot (p-1)} \tag{4}$$

where: n_i – number of realizations of the strength of temperature trends at a given level, n – total number of measurements, $\overline{\Delta T/\Delta\tau_1}$ – average strength of temperature trends from the products of measurement in the i-th row, $\overline{\Delta T/\Delta\tau}$ – average strength of temperature trends of products from all measurements, $\Delta T/\Delta\tau_{ij}$ – the j-th amount of the strength of temperature trends at level i, p – number of variances of the input factor (opening pressure of fuel injector).

In addition, the values of the reliability factor ΔF were defined as a measure of the power of a statistical test, which is the difference between the value of the Fcal statistic, calculated for the input indicator under study, and the critical value, calculated according to formula (5) [19, 26, 43].

$$\Delta F = F_{cal} - F_{cr} \tag{5}$$

The next step in the statistical analysis was a bivariate analysis to assess which of the input indicators analyzed (structure or load) had a stronger effect on the output parameter. Only those structural data that were considered crucial as a result of the univariate analysis were analyzed.

In both cases, the influence of the considered input indicator on the output indicator was considered key when the experimental value of the F_{cal} indicator was greater than or equal to the critical value of F_{cr}, obtained from the tables.

By comparing the values of reliability factors ΔFI (for the first input factor) and ΔFII (for the second input factor) (6), it was possible to assess which of the 2 input indicators (load or structural data) had a greater impact on diagnostic measures.

$$\Delta F_{I} = F_{cal\ I} - F_{cr};\ \Delta F_{II} = F_{cal\ II} - F_{cr} \tag{6}$$

Nowadays, in the digital age, online statistical calculators are popular to determine the critical size of a statistic (F_{cr}), or the significance level $\alpha(F_{cal})$, for distributions known in mathematics [31, 44]. They provide important support during statistical analysis of the products of ongoing diagnostic studies. They allow the selection of statistical analysis tools and shorten some time-consuming calculations [5, 50].

The data for harmful and toxic components in the exhaust gas (Table 4) were given in different units for different methods of determination. To avoid additional inaccuracies when standardizing the units, it was decided to compare the relative values of these parameters, calculated from relation (7). No qualitative assessment was made, only quantitative, and the trend (increasing or decreasing) was assessed, so this method of determining the data for analysis was considered sufficient

$$\mathrm{TREND} = \left|\frac{\mathrm{CO(ref)} - \mathrm{CO(unfitness)}}{\mathrm{CO(ref)}}\right| \tag{7}$$

where: CO(ref) – CO content in the exhaust gas at the reference (baseline) condition, CO(unfitness) – CO content in the exhaust gas for the analysed unfitness condition, for the selected determination method.

No error analysis was carried out for the rapidly variable exhaust gas temperature measurements, and diagnostic measures were determined from them. It would have been possible to carry out a type A standard uncertainty assessment in this case, but the statistical analyses carried out (F statistic of the Fisher-Snedecor distribution), and the synchronous averaging of the recorded signal already take this assessment into account [3].

Additionally, the measurements of the exhaust gas components taken for the analyses are the mean value. Data were obtained from several measurements at a given load point and engine operating condition. Each time, the average of several dozen readings of the measuring tools was determined. A type A standard uncertainty analysis showed no possibility of gross errors, so the results were considered statistically reliable [3].

3. Results of experiment

After testing according to the conditions described above, the results obtained were subjected to mathematical and statistical processing. As a product, reliability factor values were obtained for both univariate analysis (Fig. 14) and bivariate analysis (Fig. 15).

In parallel, the components of the exhaust gas were measured and analyzed, and their quantities were compared with the products of numerical modeling in Diesel-RK software and the results are summarized in Table 2.

The final result of the analyses was a tabular summary (Table 3) of the procedure for selecting the analyzed diagnostic tool depending on the type of damage under consideration.

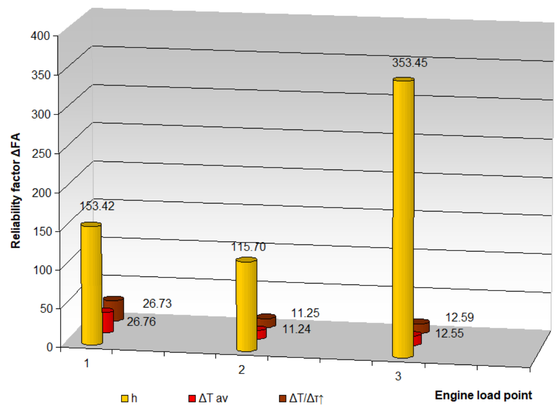
According to the results of the statistical analysis and the developed characteristics for the univariate analysis

[1] For better readability of the formula, the arrow symbol has been left out in the indication of the strength of temperature trends $\Delta T/\Delta\tau\uparrow$.

(Fig. 14), the following important general conclusions were drawn:

1. Reducing the active area of the air inlet had a significant effect on all diagnostic tools, but the specific enthalpy had the highest ΔF.
2. Limited p_{inj} pressure significantly affected ΔT_{av} and $\Delta T/\Delta\tau\uparrow$ for all analyzed engine loads.
3. The effect of limited compression ratio ε was crucial for all diagnostic tools.

a)



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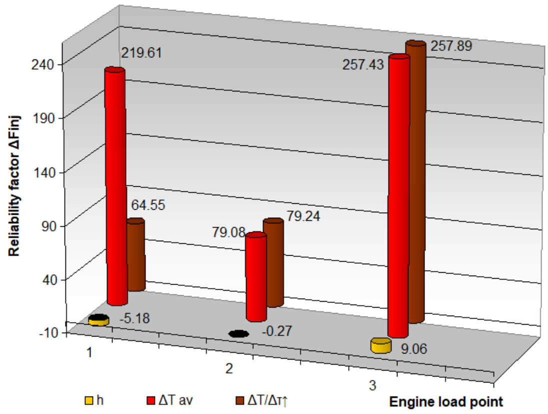


c)

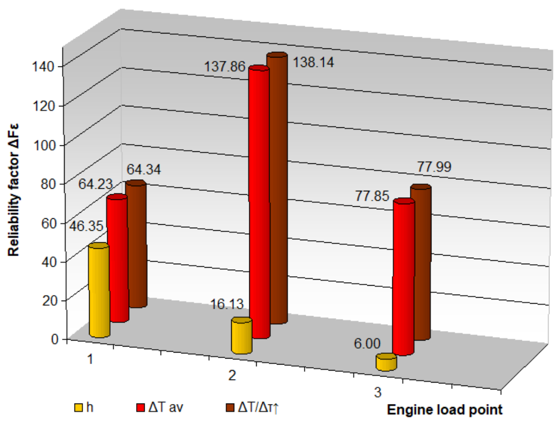
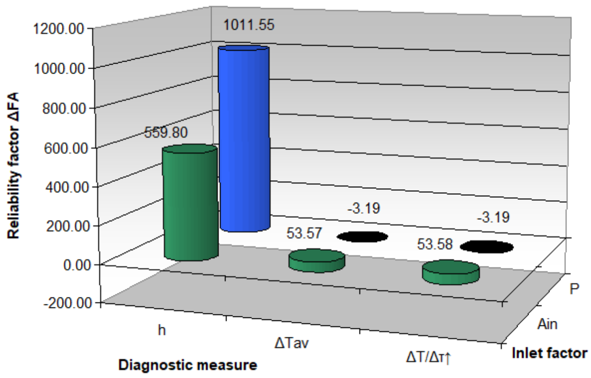
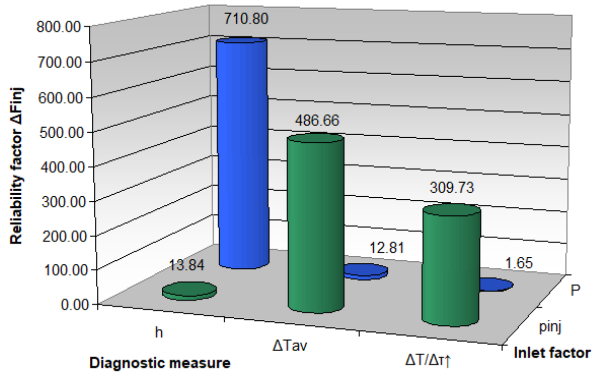


Fig. 14. Amounts of reliability factor ΔF for univariate analysis of the impact of modifications of engine load P and structure parameters: field of the active section of intake airflow A_{inj} (a), opening pressure of fuel injector p_{inj} (b), and compression ratio ε (c) on amounts of defined diagnostic tools (h, ΔT_{av} and $\Delta T/\Delta\tau\uparrow$)

a)



b)



c)

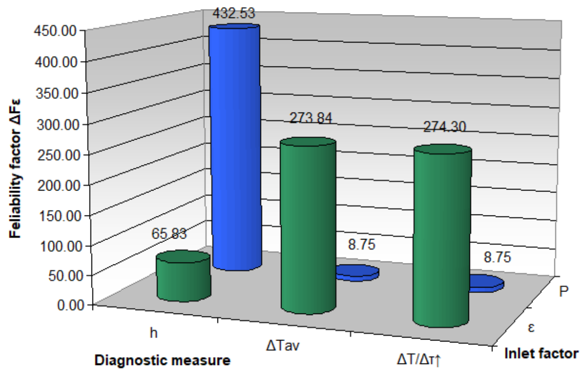


Fig. 15. Amounts of reliability factor ΔF for bivariate analysis of the concurrent impact of engine load P and structure parameters: field of the active section of intake airflow A_{in} (a), opening pressure of fuel injector p_{inj} (b), and compression ratio ε (c) on amounts of defined diagnostic tools (h, ΔT_{av} and $\Delta T/\Delta\tau\uparrow$)

The following general conclusions are made for the bivariate analysis (Fig. 15), in which the input indicators are engine structural data (A_{in}, p_{inj}, ε) against a background of varying load P:

1. Fuel injector opening pressure and compression ratio have a greater effect on $\Delta T/\Delta\tau\uparrow$ and ΔT_{av} than engine load, so reducing p_{inj} and ε results in a marked increase in turbulence in the course of rapidly changing exhaust gas temperature.
2. Both A_{in} and load have the strongest effect on specific enthalpy, which is due to the simple and simultaneous effect of these two input indicators on the amount of rapidly variable exhaust gas temperature.

Table 2. Amounts of harmful and toxic exhaust components: NO_x, NO and CO_2 for the four considered engine states, obtained by numerical modeling and bench measurements, with the trend relative to the baseline marked (rise or drop in %); (green marks indicate the trend in accordance with theoretical knowledge, red crosses – the opposite trend)

Determination method	Test conditions											
	ref	A_{in}	p_{inj}	ε	ref	A_{in}	p_{inj}	ε	ref	A_{in}	p_{inj}	ε
	Harmful component of the exhaust gas											
	NO_x				NO				CO_2			
Simulation	1523.6 ppm	1538.3 ppm	1436.2 ppm	1469.3 ppm	12.899 g/kWh	13.159 g/kWh	12.201 g/kWh	12.404 g/kWh	904.33 g/kWh	913.43 g/kWh	907.61 g/kWh	901.17 g/kWh
Trend relative to the baseline	–	↑0.96% V	↓5.74% X	↓3.56% V	–	↑2% V	↓5.4% X	↓3.84% V	–	↑1% V	↑0.36% V	↓0.35% X
Laboratory test	554.66 ppm	765.73 ppm	1059 ppm	777 ppm	538.02 ppm	742.76 ppm	917 ppm	623 ppm	4.07%	5.57%	5.8%	6.1%
Trend relative to the baseline	–	↑38% V	↑90.9% V	↓40% V	–	↑38% V	↑70.4% V	↑15.8% X	–	↑36.86% V	↑42.5% V	↑49.9% V

Table 3. Table of choice of diagnostic tool based on IC engine design parameter

Structural data \ Diagnostic tool	h	ΔT_{exh}	$\Delta T/\Delta\tau\uparrow$
$A_{in}\downarrow$	especially recommended	low relevant	low relevant
$p_{inj}\downarrow$	low relevant	especially recommended	especially recommended
$\varepsilon\downarrow$	low relevant	especially recommended	especially recommended

As can be seen in Table 2, the contents of the harmful and toxic components of the exhaust gas obtained from the simulation and during the test are presented in different amounts (ppm, g/kWh, and %). Therefore, it was decided to compare the relative amounts in percentages. In addition, it was determined whether the trend obtained during the analyses (increase or decrease in quantities) is consistent with current knowledge of the effect of defects on the composition of exhaust gas in engine systems [32]. In the case of numerical modeling of the processes occurring in the modeled engine, only part of the obtained products is consistent with knowledge. This may be due to imperfections in the program's computational algorithm, consistent with the Zeldovich model [6]. The second presumed reason is the imperfection of the model of the tested engine, in particular, the reproduction of the conditions that prevailed during laboratory tests or the technical condition of the Farymann Diesel engine.

During the laboratory tests, all of the partial loss-of-performance states resulted in increased NO_x, CO_2 and NO emissions (Table 2). In several cases, both simulation and testing agreed on the trend, but the quantities differed. It is, therefore, possible to make diagnostic inferences based on exhaust emissions as a support for the proposed method in accordance with the analysis of rapidly changing exhaust gas temperature, if possible (measurement susceptibility of the engine in operation).

Analyzing all the results obtained, the following cause-and-effect relationships between the engine malfunctions and the parameters obtained were noted:

1. Reduced active area of the air inlet resulted in a significant effect on specific enthalpy and a small effect on the other measures. However, engine load has a greater effect on enthalpy than this malfunction. An increase in all analysed components (NO_x, NO and CO_2) was noted in the exhaust gas composition.
2. Reduced opening pressure of fuel injector p_{inj} resulted in a significant effect on the strength of the temperature trend $\Delta T/\Delta\tau\uparrow$ and peak-to peak value ΔT_{av} and no effect on enthalpy. However, engine load has no effect on $\Delta T/\Delta\tau\uparrow$ and ΔT_{av}, but has a greater effect on h than this inefficiency. The composition of the exhaust gas showed an increase in all analysed components (NO_x, NO and CO_2).
3. The reduced compression ratio ε resulted in an effect on all measures but the largest on $\Delta T/\Delta\tau\uparrow$ and ΔT_{av}. However, engine load has a negligible effect on $\Delta T/\Delta\tau\uparrow$ and ΔT_{av}, but has a greater effect on h than this inefficiency. An increase in CO_2 and a decrease in NO_x and NO were noted in the exhaust gas composition.

4. Conclusions

According to the analysis, the following conclusions were drawn, according to Table 3, among others:

1. During diagnostic tests, the engine should be at the highest load, and then the specific enthalpy of the exhaust gas responds most strongly.
2. Loss of inlet duct patency is best indicated by specific enthalpy h.
3. ΔTav and $\Delta T/\Delta\tau\uparrow$ have the greatest diagnostic vulnerability to curbed pressure of injector opening. At higher engine loads, the vulnerability of these diagnoser tools is higher.
4. Defects that can affect a limited compression ratio ε are best diagnosed by ΔTav and $\Delta T/\Delta\tau\uparrow$. These measures show high diagnostic susceptibility over the entire range of analyzed load changes.
5. Inferences according to the proposed diagnoser tools can be made for measurements made with thermocouples with adequate low amounts of the time constant, on the order of a few to tens of milliseconds.
6. A valuable addition to the conducted analyses is the recording of toxic and harmful components of the exhaust gas, the rise of which indicates damage to the analyzed systems of the engine.

In the opinion of the author of this article, the proposed method, with the support of exhaust gas composition analysis, is useful in the studied scope of work. It is possible to develop this method, for example, to extend it with new diagnostic tools or to enable its use for diagnosing marine engines in operation (Fig. 16). It is necessary to adapt the existing thermocouple for fast measurement change with simultaneous acquisition of average values, so as not to disturb the existing measurement path. In order to obtain as much diagnostic information as possible from the recorded measurement signal, it is necessary to use appropriate measurement technology. It is also crucial to carry out appropriate mathematical and statistical processing of the obtained waveforms [36].

The technology for measuring the diagnostic parameters under consideration should take into account, first of all, the preparation and specially prepared thermocouple in place of the standard measurement – Fig. 16, depending on the design solution of the engine:

– in the case of a single-cylinder engine, the measurement of the rapidly variable exhaust gas temperature in the duct should take place at the shortest possible distance from the exhaust valve
– in the case of a naturally aspirated multi-cylinder engine, thermocouples should be placed directly behind each cylinder (Fig. 16b). If this is not possible, the thermocouple should be mounted in the collective duct (Fig. 16a and 16c), and in addition, the accelerometer should be placed on the head cover (or on the injector) of one of the cylinders, in order to identify successive pulses of the exhaust gas stream (temperature)
– in the case of a turbocharged marine engine, if it is not possible to measure the temperature behind each cylinder, a thermocouple should be placed in front of the turbocharger, and in addition, vibration sensors should be mounted on the heads of selected cylinders to analyze the temperature signal against the vibration signal (for the purpose as above)
– regardless of the type of engine, if possible, the composition of the exhaust gas should be measured in parallel.

The proposed method of parametric diagnostics against the background of the new requirements seems to be a good proposal: we detect malfunctions with simultaneous information about the emission of harmful and toxic compounds into the atmosphere. The method of measuring the rapidly variable exhaust gas temperature is useful when it is not possible, for example, to indicate the engines, and the values of the averaged exhaust gas temperature measured in the standard way do not give as much diagnostic information as the rapidly variable one. In the proposed method, it is clear how the malfunctions considered affect the diagnostic measures analysed and the exhaust gas composition. Thus, the cause-and-effect inference is quite straightforward for the engine operator. According to the author, the proposed method is characterized by utilitarianism, it is possible to apply it in the diagnosis of marine engines after appropriate adaptation of the existing measurement system. This is indicated by the statistical and merit analysis of the results obtained. In the era of progressive energy transition and efforts to reduce emissions of harmful compounds into the atmosphere, this is a very important issue. It is possible to develop the proposed method also for parametric analysis of engines powered by alternative fuels. Early detection of defects in engine systems is associated with both economic and environmental benefits.

a) b) c)

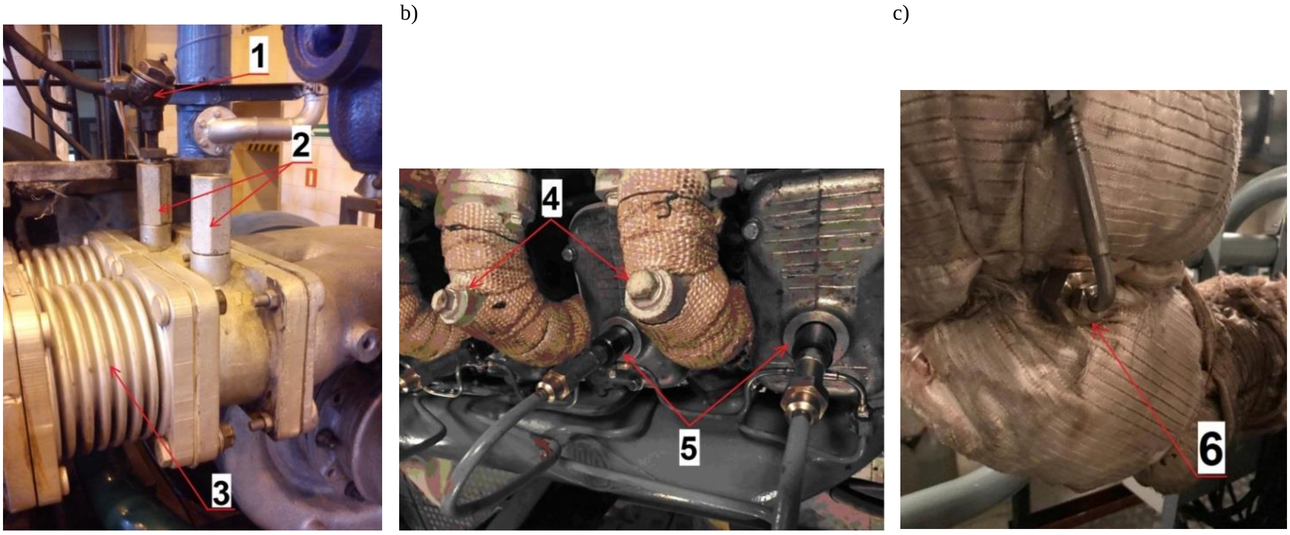


Fig. 16. View of the place of installation of a standard thermocouple for measuring the average temperature of the exhaust gas in the channel connector immediately before the turbocharger in a Sulzer type 6AL 20/24 engine (a); 1 – view of the place of installation of a standard thermocouple or pressure sensor in the exhaust gas duct of a Wola Henschel 71H6 (6R 1416) engine (b); view of the thermocouple mounting location on the exhaust gas collection duct of the Wola Henschel 71H6 (6R 1416) engine (c); 1 – standard thermocouple for measuring the average exhaust gas temperature, 2 – thermocouple mounting stubs, 3 – stress compensators in the exhaust gas duct, 4 – place allowing the thermocouple or pressure sensor to be mounted directly behind engine cylinders, 5 – fuel injectors, 6 – thermocouple for measuring the average exhaust gas temperature

Nomenclature

A_{in}	active cross-sectional area of inlet channel	F_{cal}	calculated value of F statistic
CSR	crankshaft speed rotational	F_{cr}	critical value of F statistic
F	Fisher-Snedecor distribution statistics	h	specific enthalpy

IC	internal combustion	VOCs	volatile organic compounds
MGO	marine gas oil	α	significance level
p_{inj}	opening pressure of injector	ΔF	reliability factor
PM	particulate matter	ΔT_{av}	peak-to-peak value of temperature
RMD	residual marine fuel	$\Delta T/\Delta\tau\uparrow$	strength of temperature trends
TDC	top dead center	ε	compression ratio

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