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Evaluation of the influence of the opening pressure of a marine diesel engine injector on the results of numerical simulation of the working cycle and their comparison with the results of the laboratory experiment

The article presents the results of a numerical simulation of the working process carried out in a diesel engine. In the applied utility program DIESEL-RK, the laboratory engine Farymann Diesel type D10 was implemented. A selected inoperability of its functional fuel supply system – reduced opening pressure of the injector p_{inj} – was introduced. The values of adequate diagnostic parameters were determined: working gas temperature in the cylinder T_{cyl}, exhaust gas temperature T_{exh}, combustion (flame) temperature T_{comb} and concentration of nitrogen oxides in the exhaust gas NO_x. Experimental tests were carried out on the experimental engine with the inoperative condition actually introduced, analogous to the numerical simulation, and the diagnostic parameters T_{exh} and NO_x were recorded. The results obtained by numerical simulation of the processes and during the active experiment on the experimental engine were compared.

1. Introduction

Parametric diagnostics of marine diesel engines is essential for the long-term and safe operation of a ship's engine room and power plant. It is a rapidly developing area in terms of the measurement sensors (e.g., temperature or pressure) used in diagnostic systems [3, 6, 13, 14]. An important support for these systems and the operators themselves are usable computer programs that allow numerical simulation of the processes occurring in the engine during the realized operating cycle. It is also important to determine, by means of further calculations, the values of diagnostic parameters, authoritative in the case of the occurrence of impurities or inefficiency of structural elements surrounding the combustion chamber, but also of the fuel supply system or intake air. Carrying out numerical simulations of the working process allows the selection of adequate diagnostic parameters, which, recorded during experimental tests or normal operation of a marine engine, can give the most diagnostic information about the analyzed inefficiency. This article proposes a method of determining the effect of a selected inefficiency in the functional fuel supply system of a marine diesel engine on its diagnostic parameters, according to the following steps:

1. Selection of one of the most common inefficiencies in the functional systems of marine diesel engines, based on literature data.
2. Introduction of design changes in the DIESEL-RK computer program and determination of adequate diagnostic parameters by numerical simulation of the working process occurring in a 4-stroke marine diesel engine, for the Farymann Diesel type D10 experimental engine implemented in the program.
3. Conduct an active experiment on the experimental engine's laboratory stand and determine the diagnostic parameters for the actual change in the structural design, analogous to the numerical simulation.

4. Comparison of the effect of changing the structural design parameter of a selected component of the engine's fuel supply functional system on the diagnostic parameters obtained by numerical simulation of the working process and as a result of an active experiment on an laboratory engine.

2. Results of numerical simulation of diesel engine working cycle in DIESEL-RK program

A numerical simulation of the operating process of a Farymann Diesel type D10 laboratory engine was carried out. The DIESEL-RK program for numerical simulation of thermodynamic processes occurring in a piston engine was used [7, 8, 17, 19]. The DIESEL-RK computer program in the public version is designed to simulate and optimize the thermodynamic processes of two-stroke and four-stroke engines, for all types of supercharging and for the various fuels used. The possibilities of the software allowed to implement into the program the structural (e.g. piston diameter, combustion chamber volume) and operational data (such as rotational speed of the crankshaft or type of fuel) of the laboratory engine Farymann Diesel type D10 – Fig. 1. The elementary composition of the marine gas oil (MGO) feed fuel used during the laboratory tests was entered. Calculations of the working process were carried out for two engine states: reference and for reduced opening pressure of the injector p_{inj} ($2 \cdot 10^6$ Pa less).

The choice of injector opening pressure was based on the fact that the fuel supply system is one of the functional systems of a marine diesel engine that most often malfunctions [14–16]. Analyzing the damage to marine diesel engines, the most critical functional systems are the fuel system (nearly 50% of all damage) and the working gas exchange (24.7%). In the case of the fuel supply system, injectors (41%) and injection pumps (38%) are the components most frequently damaged [15].
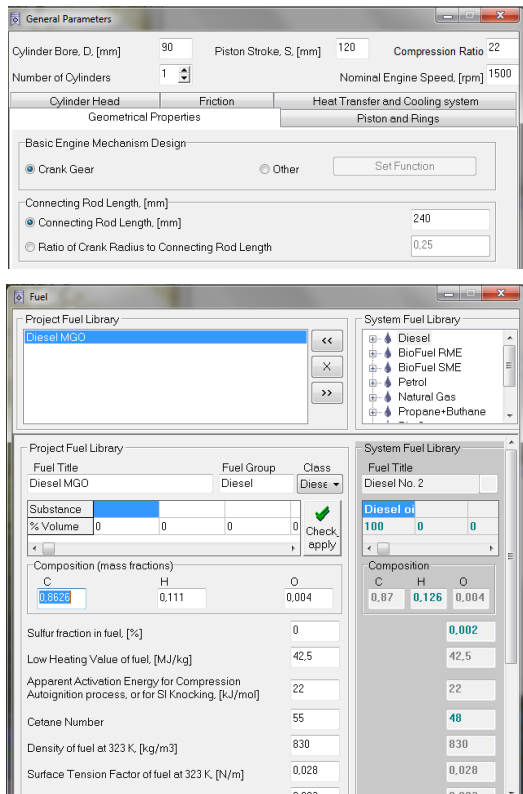
Fig. 1. View of the window of the DIESEL-RK computer program, in options: "General parameters" and "Fuel"

In his dissertation, Dr. Eng. S. Bruski presented the results of a statistical study for medium-speed engines operated on the Navy's ships [1]. The author shows that the most frequent failures happened in the fuel supply (72%), the valve train (19%) and the air supply (9%) systems. With 54% of injector failures in the fuel supply system, they accounted for 38.9% of all engine failures in operation. A research team from Vietnam, on the basis of their reliability analysis of the structural components included in the functional systems of a marine diesel engine, identified the injection system as one of all the functional systems of a marine engine that wears out at the fastest rate – each additional 500 hours of engine operation doubles the probability of damage to the components of this system [11].

Due to the subject matter of the author's research, this article presents simulation results on the following output parameters, calculated in the DIESEL-RK program [9, 10]:

- temperature of working gas in the cylinder (T_{cyl}),
- temperature of the exhaust gas in the outlet channel (T_{exh}),
- combustion (flame) temperature in the cylinder (T_{comb}),
- concentration of nitrogen oxide particles NO_x in the exhaust gas (ppm).

The results of calculations of the working process carried out in the engine implemented in the program, for the two analyzed states of the design structure are presented in graphical form in Fig. 2–5. In the case of the introduced changes in the design structure of the fuel injection system of the experimental engine, their effect on the working gas temperature in the T_{cyl} cylinder was most evident in the work stroke, in the area of the maximum value of this parameter of engine operation – Fig. 2a. The introduced change in injector opening pressure resulted in a decrease in the temperature of the working gas in the cylinder. The largest difference occurred at the maximum value of T_{cyl} and was about 25 K – Fig. 2b. The difference between the waveforms of the working gas temperature in the cylinder for the rest of the working cycle realized in the modeled engine was much smaller or did not occur at all. Also in the case of the waveforms of changes in the temperature of the exhaust gas T_{exh}, the greatest differences in the values of this parameter occur in the region of the maximum – Fig. 3a. Reduced injector opening pressure p_{inj} resulted in an increase in exhaust gas temperature by about 10 K at the maximum value of T_{exh} – Fig. 3b. The difference in the value of exhaust gas temperature T_{exh} for the two analyzed states is also visible for the rest of the engine cycle, however it is smaller – Fig. 3a. The course of changes in the temperature of combustion (flame) of gas in the cylinder T_{comb} in the case of lowering the opening pressure of the injector p_{inj} showed a slight decrease – about 6 K. This difference remained at a similar level during the whole duration of combustion of the fuel-air mixture – Fig. 4a and b. Thus, all considered parameters of the design structure of the modeled engine and changes in their values influenced variations in the values of temperatures T_{cyl}, T_{exh} and T_{comb}.
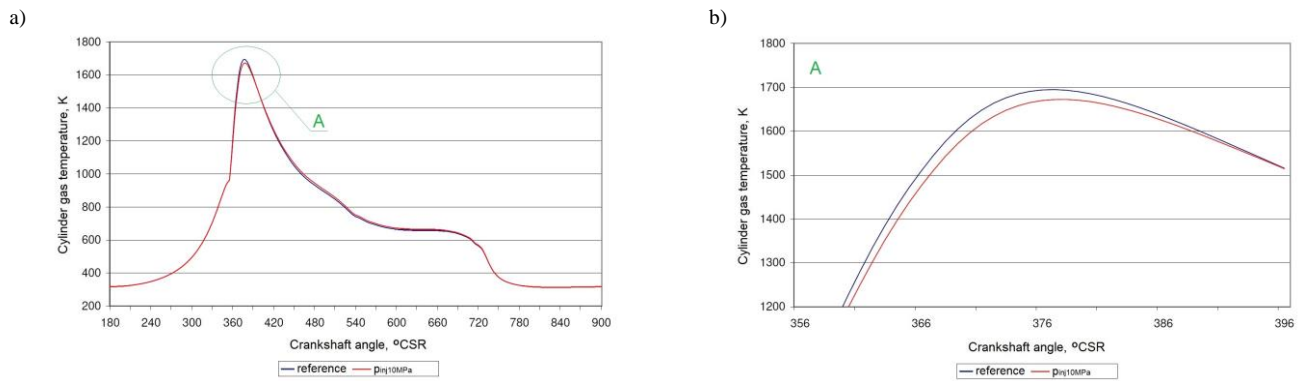
a)

b)

Fig. 2. Courses of changes in the temperature of the working gas in the cylinder T_{cyl} as a function of the angle of rotation of the crankshaft, for the whole working cycle of the engine (a) and for the range of occurrence of the maximum value of the temperature in the cylinder (b), achieved as a result of numerical simulation of the working process of the engine in the program DIESEL-RK under the conditions of introduced changes in the opening pressure of the injector p_{inj}

a)

b)

Fig. 3. Courses of changes in the temperature of the exhaust gas T_{exh} as a function of the angle of rotation of the crankshaft, for the part of the working cycle of the engine (a) and for the range of occurrence of the maximum value of the temperature of exhaust gas (b), achieved as a result of numerical simulation of the working process of the engine in the program DIESEL-RK under the conditions of introduced changes in the opening pressure of the injector p_{inj}
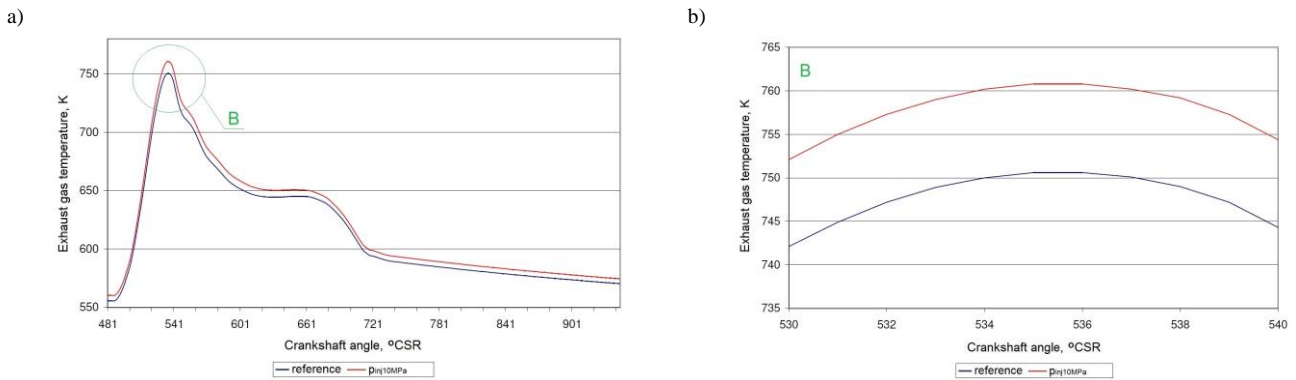
a)

b)

Fig. 4. Courses of changes in the combustion temperature (flame) in the cylinder T_{comb} as a function of the angle of rotation of the crankshaft, for the engine working stroke (a) and for the range of occurrence of the largest differences in combustion temperature for the considered states (b), achieved as a result of numerical simulation of the working process of the engine in the program DIESEL-RK under the conditions of introduced changes in the opening pressure of the injector p_{inj}
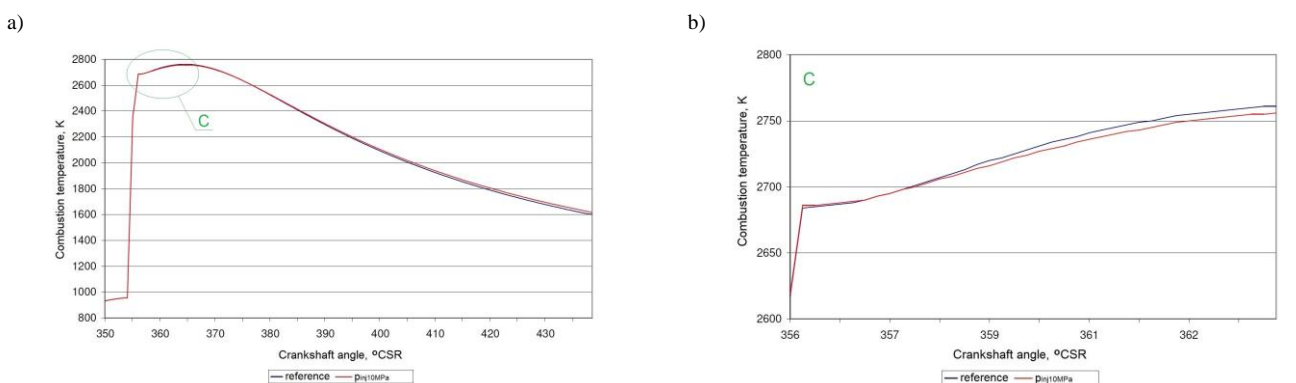
a)

b)

Fig. 5. Courses of changes in the concentration of NO_x particles in the exhaust gas as a function of the angle of rotation of the crankshaft, for the working stroke of the engine (a) and for the range of occurrence of the maximum value of the concentration of NO_x particles (b), achieved as a result of numerical simulation of the working process of the engine in the program DIESEL-RK under the conditions of introduced changes in the opening pressure of the injector p_{inj}
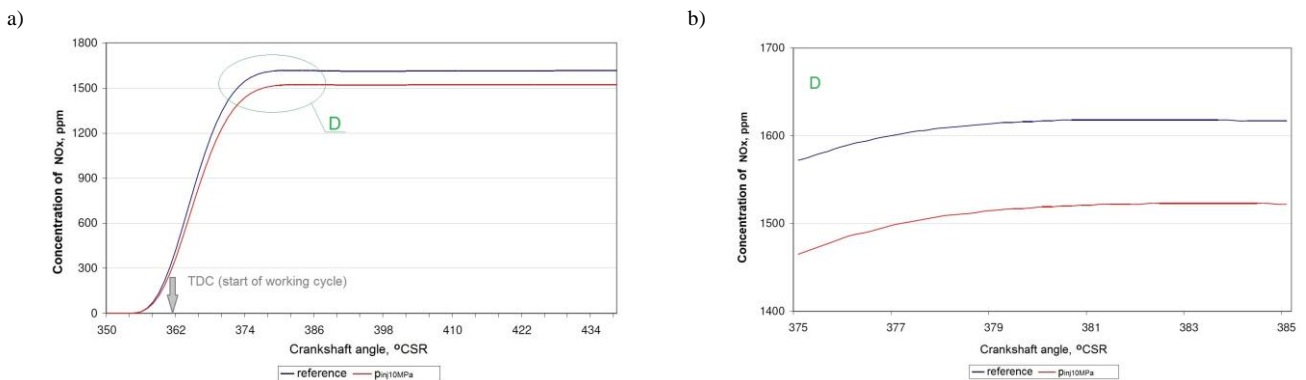
The DIESEL-RK simulation program also allowed us to deduce that for reduced injector opening pressure there is a significant effect on the value of NO_x particle concentration in the exhaust gas – lowering p_{inj} resulted in a decrease in the concentration of NO_x particles in the exhaust gas – Fig. 5. From the beginning of combustion (formation of exhaust gases), the difference in NO_x concentrations between the reference state and that for reduced injector opening pressure was about 98 ppm.

3. Results of a laboratory tests on an experimental engine Farymann Diesel type D10

The mathematical models used in computer programs that allow numerical simulation of thermodynamic processes occurring in a diesel engine contain certain simplifications (e.g., the working medium is treated as a perfect gas, and the equations of behavior do not consider mass or energy losses). Therefore, it is necessary to carry out experimental verification of simulation results, keeping in mind

that the results of laboratory tests are subject to uncertainty, which is due to interference (uniqueness) of the engine operating process and many sources of measurement uncertainty, among others, imperfection of the measurement method (measurement track), the impact of environmental conditions on the measurement result or the error of the researcher (e.g., when reading the indication of an analog instrument) [5, 12, 18]. Of course, knowledge of the thermodynamic processes and transformations occurring in the engine and in the exhaust gas channel is necessary to properly interpret the obtained measurement results and compare them with the results of numerical simulation [4].

3.1. Description of the laboratory test stand and the measurement devices used

The research was conducted on the laboratory test stand of the single-cylinder, four-stroke Farymann Diesel engine type D10 (Fig. 6), located in the Laboratory of Marine Power Plants, Faculty of Mechanical Engineering and Ship Technology, Gdansk University of Technology. The most important technical parameters of the laboratory engine include: nominal power 5.9 kW, nominal rotational speed 1500 min^{-1}, nominal torque 38 N·m, cylinder diameter 90 mm, piston stroke 120 mm, compression ratio 22:1, volume of cylinder stroke 765 cm^3.

During the research, the following were recorded: exhaust gas temperature and pressure, piston TDC signal, load current and voltage of the generator, exhaust valve opening signal, flue gas composition. In Table 1 shows the measured control parameters and the measuring equipment used during research.

A multifunctional measurement and recording module type DT-9805 from Data Translation was used to record: the quickly changing temperature and pressure of the exhaust gas and the piston top dead center signal. Matlab software was used to record the measured values. A constant crankshaft speed of 1442-1444 rpm was kept during the test. The sampling frequency was 7000 Hz. The presented research results are the average of 90 subsequent measurements recorded under the same engine operating conditions determined by the engine load, crankshaft speed and ambient parameters. A KIGAZ-310 analyzer was used to monitor the composition of the flue gas. During the tests the engine was burning marine gas fuel – MGO.

Table 1. The parameters of the Farymann type D10 single cylinder diesel engine recorded on the laboratory test stand

| Item	Parameter	Measuring device	Unit	Measurement range
1.	Exhaust gas temperature – T_{sp}	Thermocouple type K, with welded joint to 0.5 mm diameter jacket, made from Inconell	K	273–1273
2.	Exhaust gas pressure in the exhaust channel – p_{sp}	Optical pressure sensor – Optrand C12296	V	0–689475.73 Pa (0–100 psi), sensitivity 6.01·10^{-8} V/Pa (41.43 mV/psi)
3.	Engine speed (angular position ^{o}CA) – n Top dead center – TDC	Induction engine speed sensor and TDC sensor	min^{-1}	0–3000
4.	Load current of the generator – I_{tw}	Electric current meter	A	0–15
5.	Voltage at the armature terminals – U_{tw}	Voltmeter	V	0–250
6.	Exhaust valve opening signal	Gap type optoisolator with a comparator LM393	V mm	0–5 10 (gap)

a)
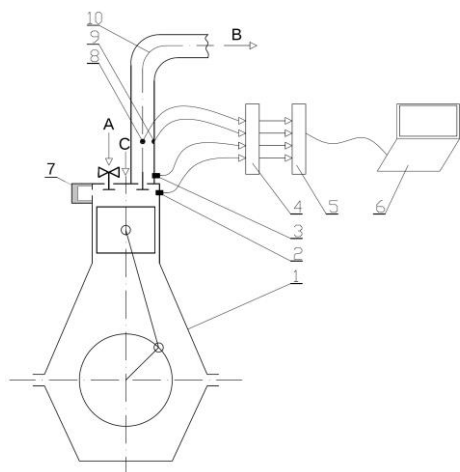
b)
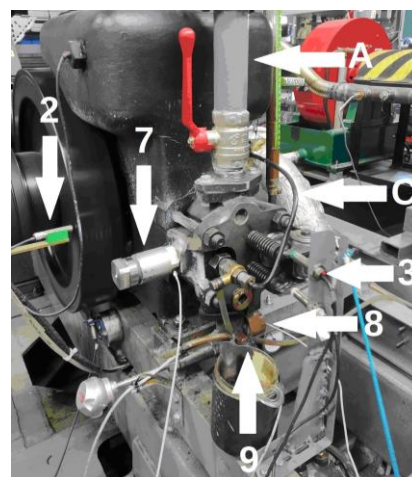
Fig. 6. a) Diagram of the laboratory test stand with the sensor mounting locations marked: 1 – Farymann D10 engine, 2 – engine rotational speed and TDC sensor, 3 – exhaust valve opening sensor, 4 – A/C converter, 5 – recorder, 6 – software, 7 – component to increase the volume of the combustion chamber, 8 – pressure sensor, 9 – water cooled thermocouple, 10 – exhaust gas channel, A – intake air with ball valve on the channel, B – exhaust gas, C – fuel line; b) view of the stand with the location of the sensors highlighted: 2 – engine speed and TDC sensor, 3 – exhaust valve opening sensor, 7 – component to increase the volume of the combustion chamber with a pressure sensor, 8 – pressure sensor, 9 – water cooled thermocouple, A – intake air with ball valve on the channel, C – fuel line

3.2. Results of the laboratory research

The experimental research was carried out on the Farymann Diesel engine type D10 (Fig. 6). Due to the limited measurement capabilities of the experimental engine, the following in-cylinder parameters were not recorded: flame temperature and the working gas medium in the combustion chamber. However, it was possible to record and compare with the result of a numerical simulation of the working process: the temperature of the exhaust gas T_{exh} and the composition of the exhaust gas (concentration of nitrogen oxide particles NO_x). The test was conducted for two different technical states of the research object. The first defined as the reference (benchmark, baseline) condition.

The second condition – partial suitability, resulting in a decrease in the opening pressure of the injector, was introduced through changes in the design structure of the injector: the thickness of the shim under the injector spring was changed. Changing the shim to a thinner one caused the spring tension force to decrease, thus simulating relaxation of the spring's structural material [2]. This is one of the most common states of operational unfitness in a marine engine. The engine under test has an injector with shims with a total thickness of δ_{inj} equal to 2.3 mm, resulting in a fuel injector opening pressure value of about 12 MPa (the value for the reference condition) – Fig. 7. During the test, shims with a total thickness of 1.8 mm were installed in the injector, resulting in a reduction of the injector opening pressure to 10 MPa, which simulated a malfunction in the fuel injection system involving too early injection of fuel into the combustion chamber.

The temperature of the exhaust gas T_{exh} values were recorded with a K-type thermocouple, with a sheath welded joint, with an outer diameter of the sheath of 0.5 mm and a time constant of 65 ms, mounted at a distance of 15 cm from the outlet valve seat. The concentration of NO_x particles was obtained by measurements in the exhaust gas channel using a KIGAZ-310 exhaust gas composition analyzer.
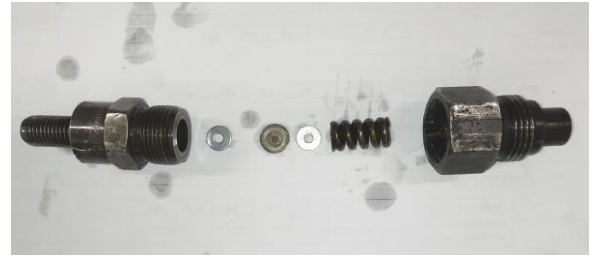

Fig. 7. View of the structural components of the injector used during the tests, including the replaceable shims under the injector spring

Table 2 shows the values obtained both by numerical simulation and measured during the active experiment, for the reference condition and for the reduced opening pressure of injector p_{inj}. In addition, the percentages of changes ΔX of these diagnostic parameters relative to the values for the engine's reference condition and the character (increase or decrease) of each change were determined, according to the relationship:

$$\Delta X = \left| \frac{X_{ref} - X_p}{X_{ref}} \right| \qquad (1)$$

where: X_{ref} – value of the diagnostic parameter for the reference condition, X_p – value of the diagnostic parameter for reduced injector opening pressure.

During simulation, the average value of the exhaust gas temperature T_{exh} for the reduced injector opening pressure p_{inj} increased by 0.9% (5.52 K), while the measurement on the experimental engine showed an approximate 4% (8.3 K) decrease in the average value of this parameter. As for the concentration of NO_x particles in the exhaust gas, the lowered p_{inj} resulted in a 95% (525 ppm) increase in concentration during the laboratory test, while the simulation showed a 5.77% (93.2 ppm) decrease in the value of this diagnostic parameter. During the active experiment, the recorded diagnostic parameters are the averaged values within one cycle of the experimental engine, while the average values too were determined for the numerical simulation – Fig. 2–5.

Table 2. Average values of the diagnostic parameters for the numerical simulation of the working process and for the active experiment for two operating states, and the percentages and character of the changes of the diagnostic parameters with relation to the reference state

Operational status	Diagnostic parameter			
	Numerical simulation		Active experiment	
	Temperature of exhaust gas T_{exh}, K	Concentration of particles NO_x, ppm	Temperature of exhaust gas T_{exh}, K	Concentration of particles NO_x, ppm
State of full suitability (reference) $p_{inj} = 12$ MPa	889.35	1614.85	478.95	553
Condition of partial suitability (reduced injector opening pressure) $p_{inj} = 10$ MPa	894.87	1521.65	470.65	1078
Value and the character of the change in the value of the diagnostic parameter	↑ 5.52 K (0.9%)	↓ 93.2 ppm (5.77%)	↓ 8.3 K (4%)	↑ 525 ppm (95%)

4. Conclusions

The achieved values of selected diagnostic parameters such as the exhaust gas temperature T_{exh} and the concentration of NO_x particles, as well as the character and magnitude of their changes relative to the reference condition, differ when we compare the values obtained by numerical simulation in the DIESEL-RK program and for the experimental test. There may be many reasons for these differences, but the following should be considered the most important:

1. Simplifications used in the computer program's calculation algorithms, such as not taking into account the real

phenomena occurring in the diesel engine and exhaust gas channel, or treating the working medium as a perfect gas.

2. The presence of many sources of measurement uncertainty during the experimental test, among others, the influence of external factors on the engine operating process and the measurement track. This factor is not considered to any degree by the numerical simulation in the computer program.

3. Phenomena occurring in the exhaust gas channel, such as: heat release in the process of expansion, delay and deformation of recorded signals, flow resistance in the exhaust gas channel depending on its structural form, technical condition of the internal surface, etc., wave phenomena occurring in the channel (interference and reflection of pressure waves), adiabatic compression of the gas column located in front of successive pulses of exhaust gas leaving the engine cylinders [6].

Programs that allow the numerical simulation of the working process occurring in diesel engines, such as the presented DIESEL-RK, can be considered useful at the stage of selecting the analyzed parameters of the engine's design structure and the adequate diagnostic parameters that will respond most strongly to the introduced changes, before proceeding to tests on a laboratory engine or under operating conditions on a ship. However, this is a very multifaceted issue that requires further research and analysis.

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