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ANALYSIS OF THE POSSIBILITY OF USING EXHAUST GAS COMPOSITION IN THE DIAGNOSIS OF A DIESEL ENGINE

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Abstract: The article analyzes the impact of malfunctions in compression-ignition engine systems on exhaust composition and cycle parameters. A naturally aspirated, single-cylinder, four-stroke Farymann Diesel D10 engine was studied, with simulated common failures. The research included laboratory experiments and computer simulations using DIESEL-RK, a tool for optimizing engine processes and thermodynamic cycles.
Malfunctions in the injection and intake systems altered the exhaust temperature, pressure rise, and maximum combustion pressure. Changes in exhaust composition were noted, especially in the nitrogen oxides (NO_x) and carbon monoxide (CO): intake throttling reduced these concentrations, while a lower injector opening pressure increased them. Laboratory and simulation results were cross-validated, ensuring reliability and providing a comprehensive analysis of the engine's condition.

Keywords: diagnostics, compression-ignition engine, exhaust emissions, computer simulation, DIESEL-RK program.

1. INTRODUCTION

This article is based on a master's thesis carried out at the Faculty of Mechanical Engineering and Ship Technology, Gdansk University of Technology. The work was aimed at determining the impact of selected defects in the functional systems of diesel engines on their operating parameters and exhaust gas composition. The author conducted a literature search on the most common defects in diesel engines [Korczewski 2022]. Based on it, the analyzed failures in the functional systems of air intake and fuel injection were selected as the most common in operation and possible on the existing laboratory bench. The background to the malfunctioning states was the engine in the reference (fully operable) state. In the first step, process simulations were carried out using the DIESEL-RK computer program to select the diagnostic parameters (including exhaust gas components) that give the most diagnostic information [DIESEL-RK 2024]. Then, for the selected damage and diagnostic parameters, experimental tests were carried out on a test bench of a Farymann diesel engine, type D10. The work allowed validation of the simulations with the results of laboratory tests for the same defects, as well as complete information on the operation of the DIESEL-RK simulation program (its usefulness for this type of research).

2. COMPUTER SIMULATION OF THE WORKING PROCESS OF A DIESEL ENGINE

For the research step concerning the simulation part, the DIESEL-RK tool was used for modeling and optimizing the work processes and the full thermodynamic cycle of internal combustion engines with all types of supercharging and the possibility of using different types of fuel [DIESEL-RK 2024].

The engine was modeled in a computer program so that the entire operating cycle occurring in it could be reproduced as accurately as possible. The engine parameters referred to specific groups, i.e. general parameters (e.g. nominal speed, cylinder diameter, cylinder stroke, fuel injection system and combustion chamber format), medium exchange system (e.g. channel lengths and diameters) and fuel parameters (e.g. chemical composition, density or viscosity).

The results of the simulation of the duty cycle of the Farymann Diesel type D10 engine are presented in the form of graphs in Figures 1 to 6. During the development of the results, the main focus was on specific parameters, such as NO_x concentration, T_{cyl} temperature and p_{cyl} pressure in the cylinder, T_{exh} exhaust gas temperature and changes in the intensity of heat release of the cylinder heat release rate (HRR).

The change in the design structure of the air intake system led to changes in the NO_x content of the exhaust gas, which are most evident at a crank angle of around 74° after top dead center (TDC) (Fig. 1). This resulted in a 20.9% increase in NO_x concentration relative to the value obtained for an efficient engine. The course of T_{exh} exhaust gas temperature was characterized by two peaks, the first occurring about 55°CA after the start of exhaust and the second at about 30° before the opening of the intake valve.

In Figure 2, which presents this phenomenon, it can be seen that with changes in the design structure of the intake system, T_{exh} is lower (-1.68%) than for the reference condition, while during the second peak it is significantly higher (+1.89%). The most significant changes also occur in the area of the maximum heat release rate (HRR) (Fig. 3). Changes in the fuel injection system resulted in a 2.92% increase in this parameter at about 6° after fuel injection (2° before the piston reaches TDC). The largest decrease, by as much as 24.62%, in p_{cyl} pressure in the cylinder was recorded when the intake was throttled (Fig. 4). For each of the 3 engine states considered, the maximum p_{cyl} fell at a crank angle of 366°. Despite the large difference between the maximum p_{cyl} in the case of the throttled intake and the reference condition (24.6%), no significant difference was recorded when analyzing the T_{cyl} temperature (0.17%).

In comparison, a reduced injection pressure resulted in a pressure drop of 2.86% while T_{cyl} was 0.93%. The highest T_{cyl} values were recorded for all cases at about 10° after the onset of maximum p_{cyl} pressure (Fig. 5). Thus, all the changes introduced in the design structure of the engine functional systems affected the changes in the values of selected parameters of NO_x, T_{cyl}, p_{cyl}, T_{exh} and HRR.

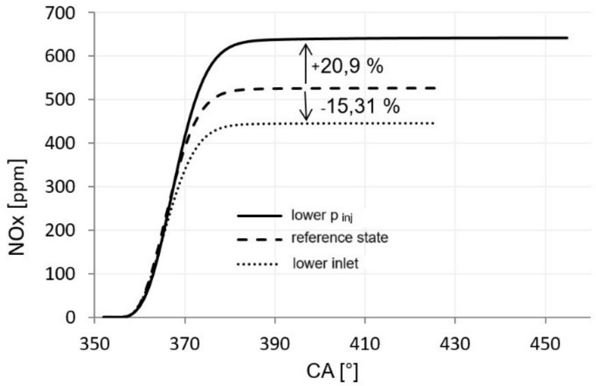

Fig. 1. Changes in the concentration of NO_x in the exhaust gas during the selected range of crankshaft rotation angle

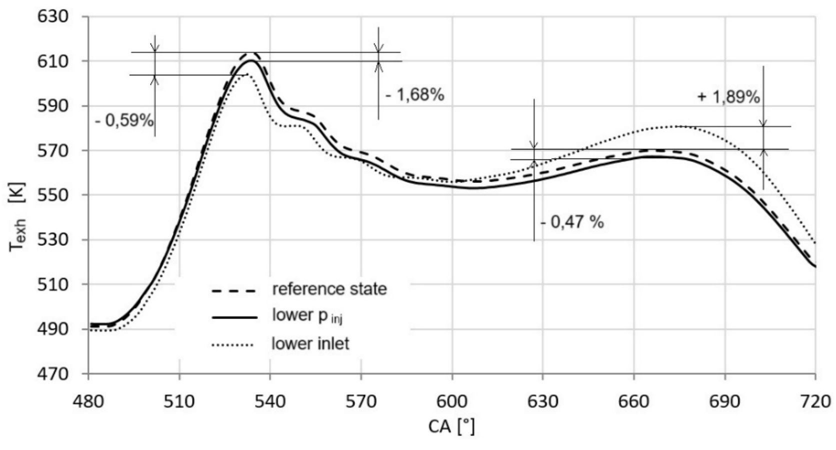

Fig. 2. Changes in exhaust gas temperature during the selected range of crankshaft rotation angle, with details of the occurrence of two temperature peaks

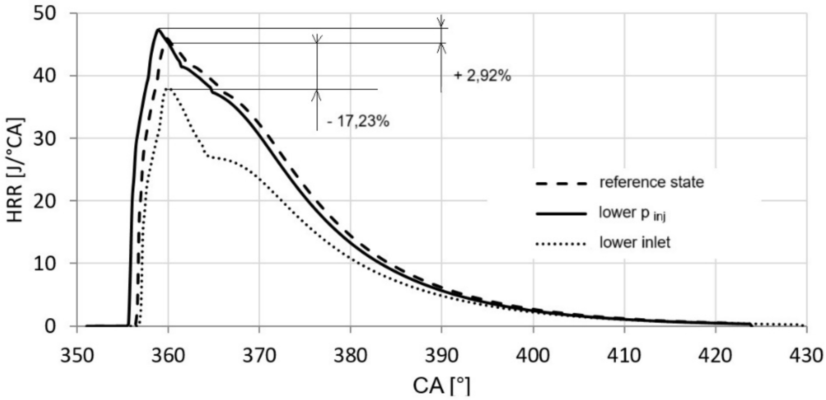

Fig. 3. Changes in the intensity of heat release during the selected range of crankshaft rotation angles

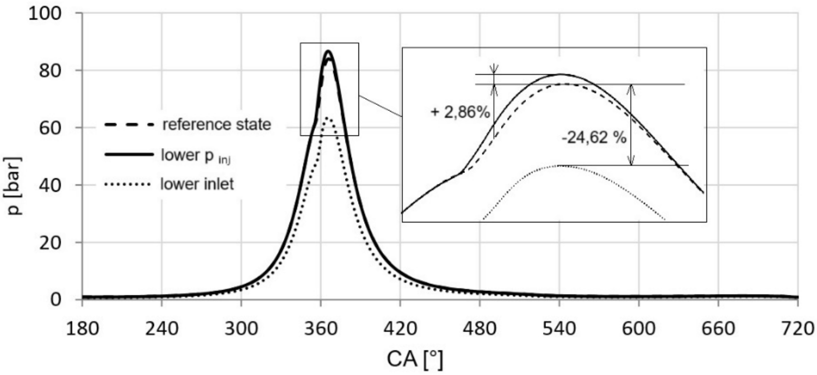

Fig. 4. Changes in cylinder pressure during the selected range of crankshaft rotation angles, detailing the occurrence of the maximum pressure moment

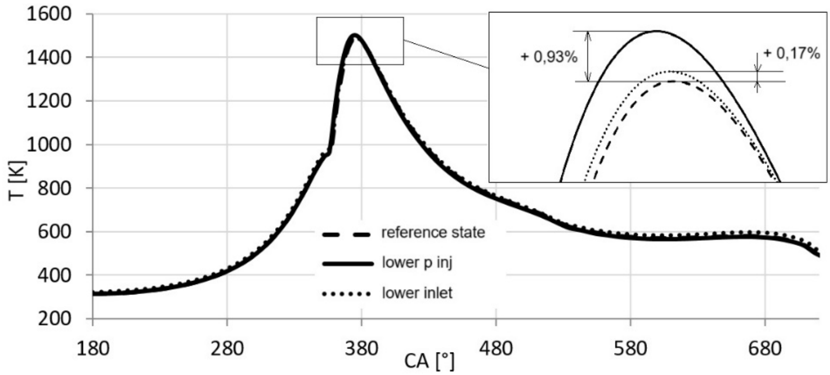

Fig. 5. Changes in temperature in the cylinder during the selected range of the angle of rotation of the crankshaft, together with a listing of the occurrence of the moment of maximum temperature

Both the highest particulate matter (PM) and CO_2 concentrations (Fig. 6) are characteristic of an engine operating with a throttled intake. These phenomena can be caused by a limited amount of oxygen reaching the combustion chamber, as well as increased airflow resistance, which further degrades the combustion conditions. In a compression-ignition engine fed with an overly rich fuel-air mixture, complete and total combustion is not achieved, which contributes to PM emissions [Reşitoğlu 2014; Prasad and Bella 2015; Puzdrowska 2023].

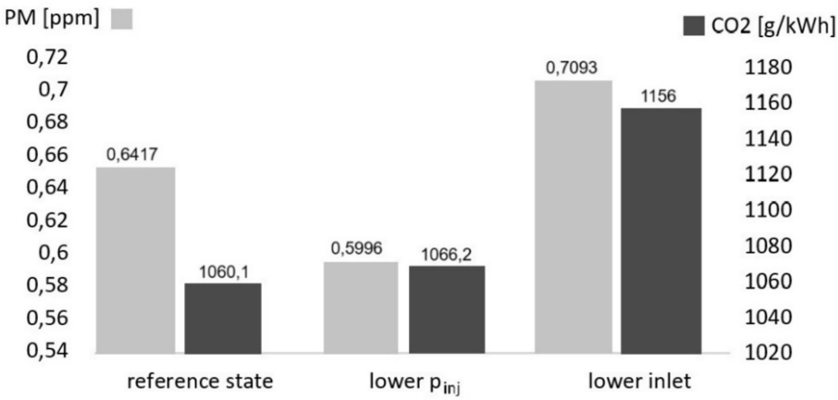

Fig. 6. Concentration of PM and CO_2 in exhaust gas depending on the engine condition

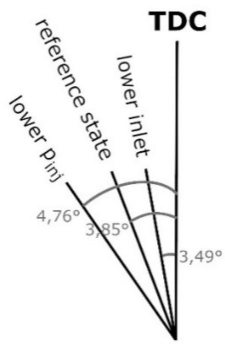

Fig. 7. Start of the combustion process depending on the technical condition of the engine (°BTDC)

The changes made to the design structure affect both the combustion process and the moment of ignition of the mixture (Fig. 7). Fuel injection into the cylinder that occurs earlier than the set injection angle will result in earlier self-ignition. The combustion time of the mixture is prolonged, which affects the much higher values of the pressure in the cylinder p_{cyl} and an increase in the rate of pressure increase ($dp/d\alpha$). The reduced cross-sectional area of the intake channel results in the supply of insufficient air to the cylinder. This results in the creation of insufficient conditions for the self-ignition of the mixture, which translates into an increased delay in the self-ignition of the fuel [Huang et al. 2019; Toma, Micu and Andreescu 2019].

Computer simulations using DIESEL-RK type software make it possible to preliminarily estimate the predicted results of the thermodynamic processes of diesel engines with a high degree of accuracy. Thanks to the possibility of modeling the parameters of the structure, it is possible to assess the impact of malfunctions of individual engine components on its operating parameters and the processes accompanying the operating cycle. The nature and magnitude of the values obtained, however, may differ from the data obtained from experimental measurements. The reasons for this may be measurement uncertainties, the simplifications used in the program's algorithms, and the inability of the program to consider the engine's technical condition and laboratory conditions [Korczewski 2022; Puzdrowska 2023; DIESEL-RK 2024].

3. EXHAUST GAS COMPOSITION ANALYSIS AND PARAMETER DIAGNOSTICS AS DIAGNOSTIC METHODS FOR THE DIESEL ENGINE

The test object was a Farymann Diesel Type D10 diesel engine, shown in Figure 8. It is an undercharged, four-stroke, single-cylinder engine powered by distillation fuel. The fuel is injected through a suppository injector into an initial vortex combustion chamber. The engine is characterized by the following parameters: nominal power 6,000W, nominal speed 1500 min^{-1}, nominal torque 38 Nm, injector opening pressure 12 MPa, cylinder chamber displacement 765 cm^3, piston stroke 120 mm, cylinder diameter 90 mm, and connecting rod length 225 mm.

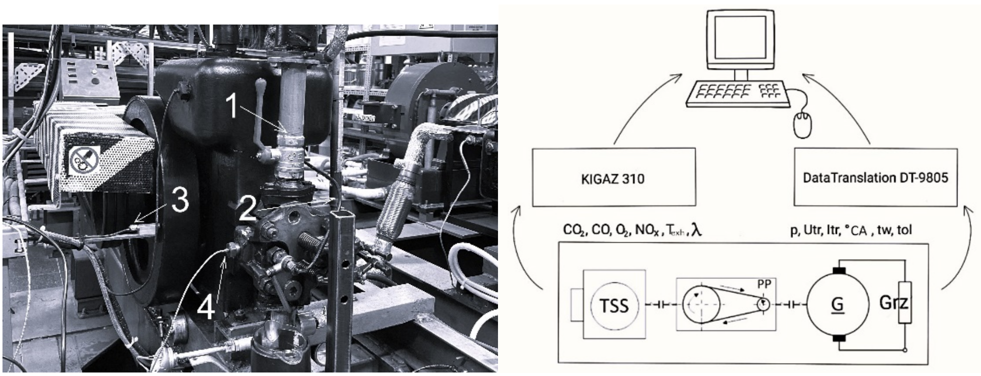

Fig. 8. View and measurement diagram of Farymann Diesel engine type D10: 1 – air intake, 2 – fuel supply, 3 – rotational speed sensor, 4 – cylinder pressure sensor, TSS – Farymann Diesel engine type D10; PP – belt transmission; G – DC generator; GRZ – heater system

Source: [Korczewski 2022].

Monitoring of engine operation was made possible through the use of measuring apparatus, which included a DataTranslation DT-9805 series ECON measuring instrument and a Kigaz 310 exhaust gas analyzer. The Kigaz 310 analyzer, with the help of sensors in the probe, records gas composition, pressure, temperature and calculates the current excess air ratio [DT9805 Technical Data Sheet 2010; Kigaz Technical Data Sheet 2015]. The calculation performance is determined by a sampling frequency of 10 kHz, with the data being averaged over 70 consecutive recorded measurement points.

The engine load changes were made according to the screw characteristics, in accordance with the engine's control capabilities: P_1 = 1040 W, n_1 = 1200 min^{-1}, P_2 = 1350 W, n_2 = 1250 min^{-1}, P_3 = 1600 W, n_3 = 1270 min^{-1}, P_4 = 1890 W, n_4 = 1300 min^{-1}, P_5 = 2300 W, n_5 = 1380 min^{-1} [Rychter and Teodorczyk 2006; Korczewski 2022]. The screw characteristic represents the operation of the ship's main engine driving a fixed pitch screw. The change in engine load is realized according to the dependence of the power required on the speed of the crankshaft represented by a third-degree parabola [Puzdrowska 2023]. For each characteristic point, the DT-9805 module made two records, from which average values were extracted.

In order to study the effect of modifications to the design structures of selected engine components on parameters characterizing engine operation, two states of malfunction were simulated on a laboratory bench. The first modification was the removal of the shim that adjusts the spring in the injector, resulting in a reduction in the opening pressure of the fuel injector from 12 MPa to 10 MPa. This was to simulate a malfunction in the injection system components, undesirable due to the engine's loss of power and increased emissions. The second simulated malfunction was to reduce the cross-sectional area of the air intake duct (throttling the intake) to reflect the real conditions of a fouled air filter. In order to assess the impact and extent of the changes caused by the above malfunctions, measurements of the Farymann Diesel D10 engine in a reference condition were performed as a reference for the results obtained [Merkisz, Piaseczny i Kniaziewicz 2016].

4. RESULTS

The increase in power ratio (effective N_e to nominal N_n) and torque accompanying the increase in load results in a decrease in O_2 concentration in each case (Fig. 9). Increasing the fuel amount while the air volume remains constant contributes to a decrease in the excess air ratio, λ. This is associated with a decrease in the concentration of O_2 contained in the fresh charge, which reacts with elements in the fuel (S, C, H, N) to form complex chemical compounds [Prasad and Bella 2015; Alper Yontar 2020]. After modifications were made to the structural design of the fuel injection system, increased oxygen (O_2) emissions were recorded at an average of 5.55% compared to the emissions accompanying the engine's full efficiency condition. Operation with an inoperative intake system is characterized by reduced emissions of this component by an average of 4.3%. The nature of the curves showing the dependence of oxygen content in the exhaust as a function of increasing load decreases dramatically when the cross-section of the intake duct is reduced.

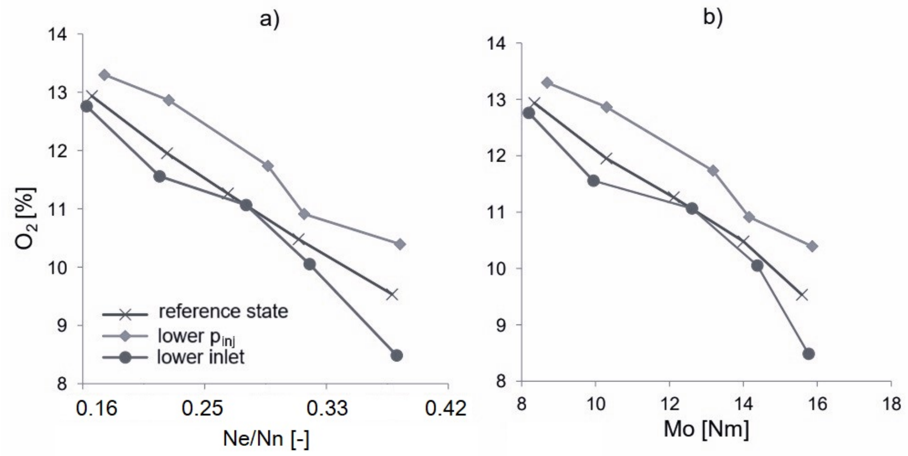

Fig. 9. Concentration of O_2 in the exhaust gas depending on the engine power ratio (a) and torque (b)

The results showed that increasing the fuel volume with an unchanged air supply results in an increase in carbon monoxide (CO) emissions (Fig. 10). Analysis of the results of CO emissions for an engine in a state caused by a malfunction of the injection system significantly causes an 11.77% increase in the average value of this parameter relative to a fully operational engine. The throttled intake, caused by a dirty air filter, in turn, results in a reduction in the carbon monoxide emissions by an average of 12.3%. The engine reacted much more smoothly to the initial change in load after being put into the inoperative state, compared with the initial section of the curves to the CO spike for the fully operational engine.

The presence of CO in the exhaust gas is mainly the result of burning rich fuel mixtures or locally enriched fuel mixtures. CO is formed from the carbon contained in the fuel as a result of the combustion reaction. If there is an insufficient amount of oxygen supplied with the intake air, the combustion process will be incomplete, i.e. the reaction product will not be carbon dioxide (CO_2) [Kniaziewicz 2019]. The combustion process is also affected by different chamber conditions, such as temperature and pressure. The introduction of turbulence and the duration of combustion can also be a direct cause of incomplete combustion. CO is also formed in the exhaust system as a result of partial oxidation of the hydrocarbons. Emission levels are influenced by the quality and composition of the fuel burned and, more precisely, the percentage of carbon (C) [Prasad and Bella 2015; Syafiq et al. 2017; Jaichandar, Samuelraj and Sathish Kumar 2019].

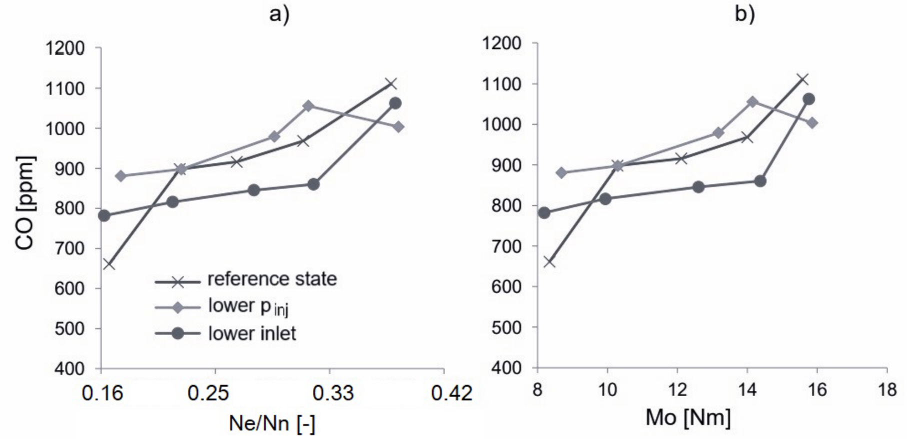

Fig. 10. Concentrations of CO in the exhaust gas rely on engine power ratio (a) and torque (b)

As with the curves describing the percentage of oxygen in the exhaust gas, a decreasing trend in NO_x emissions with increasing load is noted (Fig. 11). The main mechanism responsible for the formation of NO_x in a diesel engine is the Zeldovich thermal mechanism. It describes the formation of NO_x when excess oxygen is present at high local temperatures, above 1600–1800 K.

The oxidation process proceeds most efficiently with excess oxygen available in the combustion chamber. Among other things, NO_2 is formed when NO is oxidized by the oxygen present in the air. On the other hand, when NO_2 is oxidized, the compound is broken down into NO. It goes without saying that, in addition to temperature changes in the cylinder, NO_x concentration is also affected by changes in engine load. When the engine load is increased, the stoichiometric ratio of air and fuel is reduced accordingly. This therefore means that the oxygen concentration also decreases, which results in a decrease in the number of oxygen atoms that can react with the nitrogen molecules [Prasad and Bella 2015; Alper Yontar 2020]. The rate of NO_x formation is maximized by increasing the temperature and oxygen concentration [Rychter and Teodorczyk 2006].

However, the process proceeds most efficiently with excess oxygen available in the combustion chamber. Increasing the engine speed and load results (in the case of a diesel engine) in a decrease in the chamber's fresh air filling [Prasad and Bella 2015; Syafiq et al. 2017; Sugiarto et al. 2020], which leads to the conclusion that the lowest NO_x emissions can be observed at the engine load occurring at 1380 min^{-1}, with the highest at 1200 min^{-1}. The measurement points obtained during the tests of the engine with inoperative injection are characterized by larger deviations from the trend line than the points obtained for the next two engine states. Relative to the emissions accompanying the fully operational state of the engine, the faulty fuel injection system resulted in increased NO_x emissions by an average of 6.69%, while the throttled intake system contributed to reduced emissions of this component by an average of 24.52%.

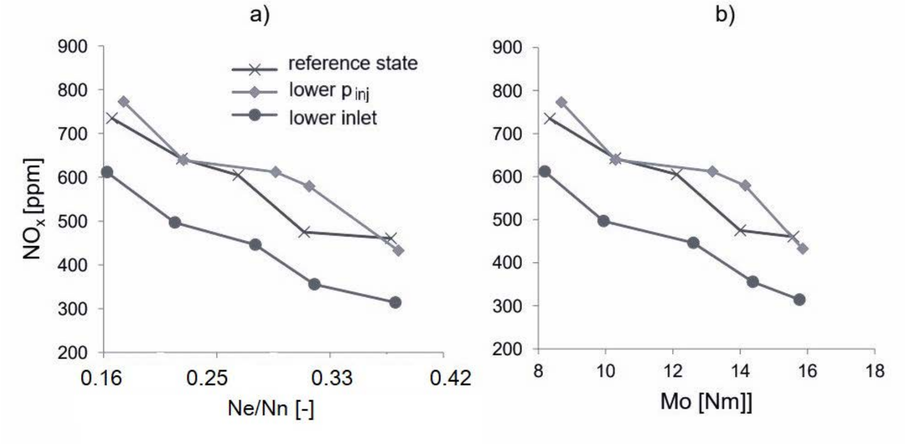

Fig. 11. Concentration of NO_x in the exhaust gas rely on engine power ratio (a) and torque (b)

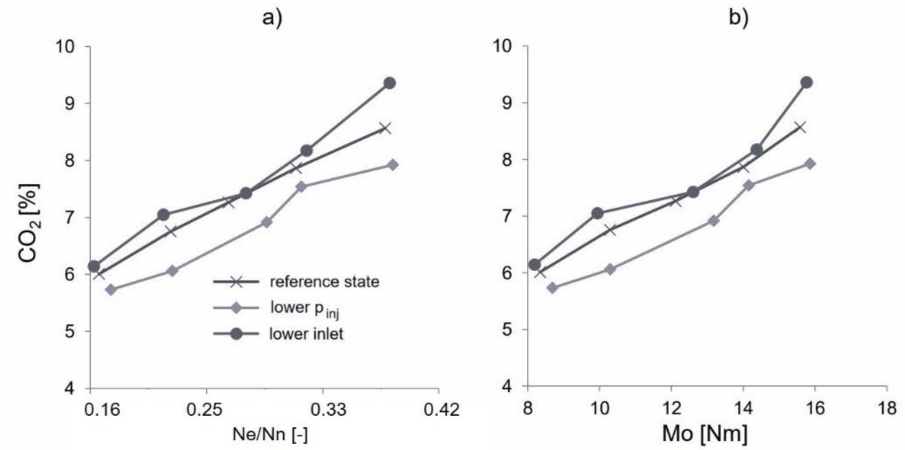

Fig. 12. Concentration of CO_2 in the exhaust gas rely on engine power ratio (a) and torque (b)

Although carbon dioxide (CO_2) is a harmful rather than toxic substance, its concentration in the flue gas needs to be monitored. It is a product of complete combustion, i.e. oxidation of carbon monoxide (CO) [Toma, Micu and Andreescu 2019]. The CO_2 content in the exhaust gas increases as the engine load increases

(Fig. 12). This has to do with supplying a higher amount of fuel, as free oxygen reacts with the carbon in diesel fuel to form this chemical compound [Prasad and Bella 2015; Syafiq et al. 2017; Kniaziewicz and Zacharewicz 2019; Abdellatif et al. 2020].

The analysis of the obtained results of CO_2 emissions highlights that, compared to the reference state, an engine with an inoperative injection system emits an average of 6.26% less, while an engine with an inoperative intake system is characterized by an average of 4.38% more emissions.

Analyzing the emissions of the engine tested in two states of malfunction led to the conclusion that the fastest rate of increase in the proportion of CO_2 in the exhaust gas is characterized by the engine in the state of malfunction caused by a throttled intake (0.00257%/W). The fastest rate of increase in CO_2 concentration is associated with the fastest reduction of O_2 content in the exhaust gas (-0.00342%/W), which indicates an effectively occurring total combustion reaction, which was not observed when operating with reduced injector opening pressure. Lowering the injector opening pressure results in a decrease in NO_x concentration by $0.291 \cdot 10^{-6}$%W.

The key parameter affecting the concentration of toxic and harmful compounds in the exhaust gas is the excess air, λ. The values of the λ parameter provided by the KIGAZ 310 Exhaust Gas Analyzer are calculated on the basis of the percentage of individual components of the exhaust gas. These values may differ from those obtained by measuring the mass flow rate of air in the intake manifold and the fuel injection system supplied. The values of λ obtained are indicative values of an auxiliary nature for diagnostic analysis of the engine. The analysis of indicative changes in λ reproduces the nature of the combustion process regardless of the chosen method of its development.

Reducing the injector opening pressure increased λ by an average of 6.68%, while in the case of malfunctions related to the intake system, values lower by 4.15% were recorded than for the full efficiency condition (Fig. 13). The higher λ values at reduced injection pressure are also largely due to the poorer performance of the fuel atomized in the combustion chamber. The necessary conditions in the engine compartment for proper combustion require operation on a lean mixture, therefore the enrichment of the fuel-air mixture is not conducive to an environmentally benign combustion process [Jaichandar, Samuelraj and Sathish Kumar 2019; Alper Yontar 2020].

A reduction in the amount of air in the combustion chamber leads to insufficient fuel combustion, more particulate matter in the exhaust, and an increase in the exhaust gas temperature t_{exh} (Fig. 14). During the tests, as the load increased, the excess air decreased, resulting in an increase in t_{exh}. The faulty injection system contributed to a decrease in t_{exh} by an average of 3.11%, while the faulty intake system resulted in an average 9.63% increase in this parameter.

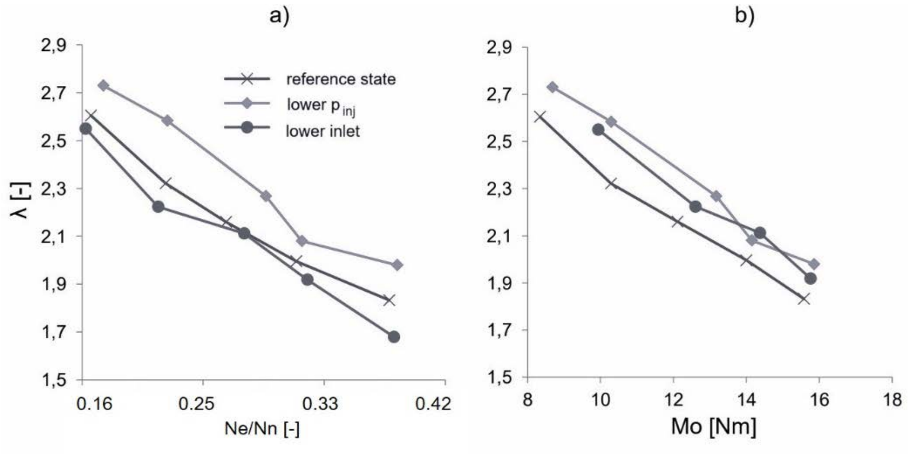

Fig. 13. Excess air ratio as a function of engine power ratio (a) and torque (b)

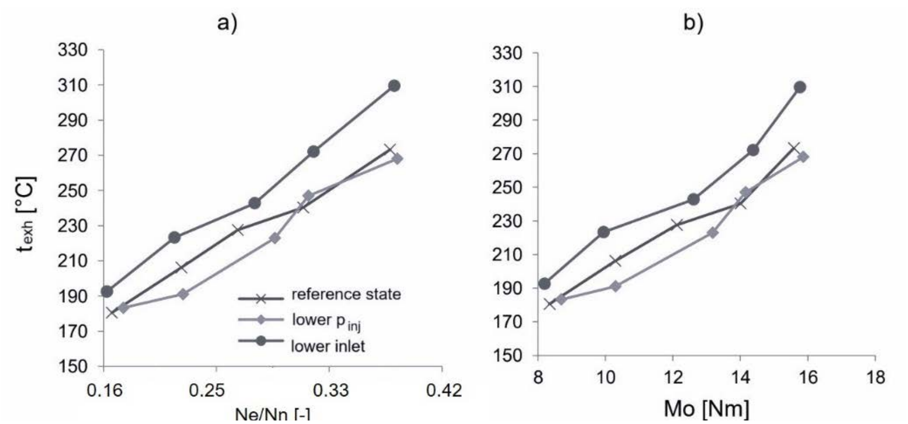

Fig. 14. Exhaust gas temperature as a function of engine power ratio (a) and torque (b)

Analyzing the emissions of the engine tested in two states of malfunction, it was concluded that the fastest rate of increase in t_{exh} was characterized by the engine in the state of malfunction caused by a throttled intake (0.094%/W). The increase in t_{exh} correlated with the fastest decrease in λ (-0.000712%/W), while the richer mixture was the reason for generating more heat. In addition to providing oxygen for combustion, air also acts as a cooling medium. More air helps cool the exhaust gas and the cylinder [Rychter and Teodorczyk 2006; Prasad and Bella 2015; Syafiq et al. 2017].

Running the engine on a lean mixture is characterized by a higher combustion temperature, which is one of the main causes of NO_x. The results obtained confirm the general relationship between the value of excess air and NO_x emissions.

The poorer the air-fuel mixture, the higher the NO_x content in the exhaust [Alper Yontar 2020; Tamilvanan et al. 2022; Puzdrowska 2023].

The dependence of CO and NO_x emissions on λ is shown in Figure 15. As the load increased (the excess air ratio decreased), CO emissions increased and NO_x emissions decreased. The coefficient of determination describing the rate of increase in nitrogen oxides and carbon monoxide emissions depending on changes in the excess air ratio can be considered as a parameter to help in the diagnostic analysis of the engine. An engine with a malfunctioning injection system is characterized by higher increments in carbon monoxide emissions and almost three times lower reductions in carbon monoxide emissions with changes in load than an engine in the reference condition.

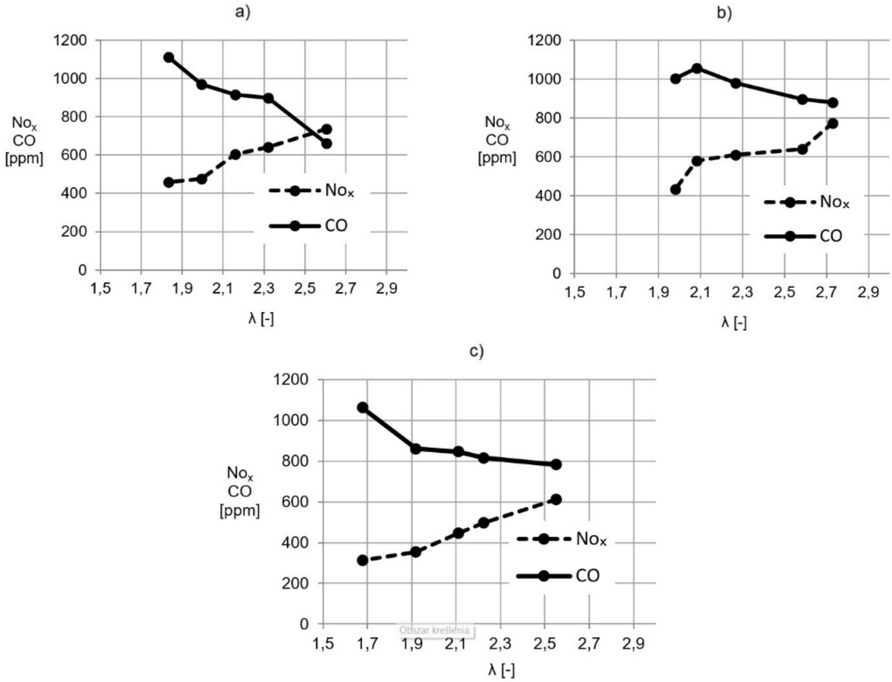

Fig. 15. Concentration of nitrogen oxides and carbon monoxide in the exhaust gas depending on the excess air ratio: reference condition (a), reduced injector opening pressure (b), and throttled intake (c)

The maximum pressure of the working medium in the cylinder was recorded at 9.96 MPa when the engine was running at full efficiency. When the injector was opened at 10 MPa, it was 12.36 MPa, while with the intake throttled it reached 10.975 MPa. Compared to the engine's reference condition, the combustion chamber pressure was found to increase by 24.1%, respectively, at reduced injection pressure. The minimum combustion chamber pressures recorded for the full efficiency condition, for reduced injection pressure and for throttled intake were 0.304 MPa, 2.117 MPa and 1.59 MPa, respectively. The effect of the change in the parameters describing the combustion of the gas-air mixture is also more than a threefold increase in compression work and a twofold increase in expansion work. With the reduced cross-section of the intake duct, an increase in pressure of 10.19% was recorded relative to the reference condition, and the work of compression and expansion of gas in the cylindrical chamber more than doubled.

When increasing the engine load, the maximum and minimum pressures in the combustion chamber increased, which agrees with the generally existing knowledge on the subject. For the P5 load point for the full efficiency condition, the maximum pressure was 10.31 MPa and the minimum pressure was 0.335 MPa. It is worth noting that for the first malfunction condition (reduced injection start pressure), the maximum and minimum pressures were 13.44 MPa and 2.897 MPa. The maximum and minimum combustion chamber pressures for the second malfunction condition caused by a throttled intake were 11.225 MPa and 1.535 MPa.

The pressure in the combustion chamber and the derivative of the pressure relative to the derivative of the crankshaft rotation angle dp/dα are two important parameters describing the combustion process [Korczewski 2022]. On the basis of 5 consecutive load changes, the averaged moment of occurrence of the maximum pressure increment was estimated for each of the distinguished 3 states of efficiency of the studied engine (full efficiency state and 2 states of inefficiency). The maximum pressure increment occurs at the full efficiency state of the engine at about 358.41°CA, at a reduced injector opening pressure at about 356.42°CA, and at a throttled intake at about 358.13°CA. It is important to note that the pressure reached its maximum value with the full condition at about 7.67°CA after TDC, with the reduced injector opening pressure at about 6.71°CA after TDC, and with the throttled intake at about 8.14°CA after TDC.

5. CONCLUSIONS

It has been confirmed that engine malfunctions have a significant effect on engine operation, which is evident in the change in concentrations of toxic substances in the splines, such as NO_x, CO and PM. For an engine operating in each of the three states, for the same screw characteristic points, reduced injector opening pressure from 12 MPa to 10 MPa increased NO_x concentrations by about 7% and CO concentrations by 11.7%. The malfunction associated with the throttled intake, on the other hand, contributed to a decrease in NO_x emissions by about 24.5% and CO concentration by 12.3%.

It was proved that most of the obtained experimental data coincided with the results of the numerical test in the DIESEL-RK program, which proves that properly applied computer software for simulating thermodynamic processes occurring in the engine is able to adequately represent real processes.

The paper shows that, in addition, the parametric analysis carried out allows more accurate identification of the source of engine malfunctions than the analysis of exhaust gas composition alone. With the same engine settings set, a reduced injector opening pressure by 2 MPa leads to an increase in cylinder pressure by 2.4 MPa and a pressure build-up rate of 0.305 MPa/°CA. The smaller cross-section of the inlet duct is the cause of twice the pressure increase (compared to the first structure change) in the cylinder by 1.015 MPa while the dp/dα parameter decreases by only 0.03 MPa/°CA. Both damage simulations contributed similarly to the increase in expansion pressure, compression work and expansion work, so these parameters could only contribute to drawing more accurate conclusions about the machine's condition when juxtaposed with other data. The amount of air and the characteristic of fuel atomization (i.e. injection start, degree of fuel atomization, droplet diameter and velocity) affect the course of heat generation during combustion, and thus parameters such as maximum in-cylinder pressure and rate of pressure increase. Less air (clogged filter) or fuel (defective injector) results in the supply of less combustion energy, resulting in lower maximum pressure and lower indicated power [Korczewski 2022].

The utilitarian nature of the work indicates the applicability of the simulation and diagnostic studies for engines in service. The method can be developed by analyzing other damage or supplementing it with other measurement techniques, such as vibration [Madej 2009].

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