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Jacek CABAN*
University of Life Sciences in Lublin
28 Głęboka, 20-612 Lublin, Poland
Paweł DROŹDZIEL, Piotr IGNACIUK, Paweł KORDOS
Lublin University of Technology
36 Nadbystrzycka, 20-618 Lublin, Poland
**Corresponding author*. E-mail: jacek.caban@up.lublin.pl

THE IMPACT OF CHANGING THE FUEL DOSE ON CHOSEN PARAMETERS OF THE DIESEL ENGINE START-UP PROCESS

Summary. For internal combustion engines, many faults relating to the combustion process can occur, which affect the engine technical condition, its electrical equipment, the natural environment, etc. This article presents the results of the influence of the regulatory factor, which was the fuel dose (3 dose values), on selected parameters of the start-up process at constant settings of other control parameters (fuel injection advance angle and injection pressure). The tests of the start-up process were carried out on a four-stroke single-cylinder diesel engine. In this study, the results of the following electrical start-up parameters were analyzed: the maximum current consumed by the starter, difference of voltages on the battery before and after the start-up, voltage drop on the battery at the beginning of the start-up, average power of the starter, starter operation time, and the maximum pressure value in the first combustion cycle.

1. INTRODUCTION

The diesel engine owing to its efficiency and ability to generate high torque is used commonly for different vehicles, agricultural tractors, stationary equipment, ships, and aircraft [1]. Compared with the spark-ignition engine, compression-ignition engines have some advantages such as reliability, fuel efficiency, larger power range, longer lifetime and maintenance period, better torque characteristics, and higher power density [2]. Humanity has been using motor vehicles for over 100 years [3]. Nowadays, there are more types of propulsions and fuels in road transport than previously [4]. Engine performance of any kind of road vehicle is considered a fundamental parameter when selecting or comparing vehicles [5]. Along with the progress of individual modes of transport in the 1990s, warning signs of the environmentally negative effect of various modes of transport occurred [6]. All sides in the transport service are trying to improve vehicle fuel consumption, which is the biggest part of the energy consumption in transport [7]. Despite the fact that there are limitations to the entrance of vehicles with diesel engines in city centers, the position of this type of engine seems still safe, especially in the area of so-called off-road vehicles and for powering various types of machinery and equipment as well as building machinery or agricultural tractors. For these reasons, wherever heavy loads and high durability and efficiency of the engine are required, the diesel engine will still be the main source of powertrain. The evolution of fuel injection systems has led to significant improvements in the performance of small and medium supercharged direct injection (DI) diesel engines [8]. The diesel is considered an environmentally friendly engine mainly owing to its reduced CO_2 emissions, as a consequence of its low consumption [9]. Moreover, the increasingly restrictive emission standards have been met thanks to the continuous development of novel technologies for combustion control and exhaust gas after-treatment [9].

For internal combustion engines, many faults relating to the combustion process can occur [10]. In short, there are faults such as leakage or coking of the fuel injection system, valve leakage, and serious wearing between the piston and cylinder liner [10]. The characteristics of the start-up are affected by all the features of the engine system, which determine the process of formation and auto-ignition of the fuel-air mixture. On the basis of many research tests [11 - 19], it was found that the majority of damage and disturbance in the operation of engines is related to the timing system, the injection system, e.g., injectors and injection pumps, or the supercharging system. The technical condition of the starting system is also important. Nevertheless, one of the critical problems of this type of engine is related to the difficulties for starting at cold conditions, particularly in places where the ambient temperature is below 0°C [20]. In addition, the impact of various factors on start-up properties may depend on several factors at the same time [1].

The start-up of the combustion engine starts when the electrical circuit of the starting system closes. Then, by means of the coupling mechanism of the starter pinion, the teeth of the flywheel ring engage, which results in the engine crankshaft engaging. This is related to overcoming the resistance of movement of moving parts of the internal combustion engine, and this is manifested in the form of the maximum value of the current consumed by the starter at the beginning of the start-up. Phenomena occurring in the course of starting a combustion engine are complicated and depend on a sequence of factors [21].

The diesel engine start-up process is a phenomenon focusing the attention of many researchers, as evidenced by a large number of scientific works [14, 18, 22 - 27]. Abramek [22] presented the results of the exhaust gas scavenging testing for the diesel engine start-up speed. Ambrozik et al. [23] presented the results of tests on the fuel impact on emissions of harmful components of the exhaust gas during cold and hot diesel engine start-up. They stated that the amounts of the exhaust gas toxic components during the cold engine start-up are much higher in comparison with those during the start-up of the pre-heated engine [23]. The effects of unburned hydrocarbon recirculation on ignition and combustion during diesel engine cold starts were investigated by Cui et al. [24]. An analysis of the chemical kinetics showed that the reaction intermediates present in unburned hydrocarbons, such as ketohydroperoxides, were the most significant factor in enhancing the LTR during non-firing cycles [24]. At the same time, the substantial heat capacity of unburned hydrocarbons suppressed the LTR for higher recirculation rates [24]. Desantes et al. [14] studied the influence of nozzle geometry on ignition and combustion progression under glow-plug aided cold start conditions in an optically accessible engine. Mikulski et al. [18] investigated the capability of using diesel–biodiesel mixtures containing up to 75% bio-components in a modern CRDI engine without any operational issues. Weilenmann et al. [27, 28] investigated the influence of ambient temperature on cold-start excess emissions of both gasoline/diesel engines in vehicles, at three ambient temperatures (23, -7, and -20 °C). Pacaud et al studied the effect of low-compression ratio of the engine to start under ambient conditions and cold start-up (down to -25 °C). The effects of combustion chamber design such as spray position vs glow plug show a great potential regarding behavior in cold conditions, notably to reduce again start delay in such conditions [25]. Payri et al. [26] investigated the behavior and stability of the combustion when multiple injection strategies are applied in the idle phase (900 rpm), just after cold starting of a low-compression ratio (15:1) single-cylinder DI diesel engine.

As commonly known during the engine start-up, a number of negative phenomena occur, which affect the engine technical condition, its electrical equipment, and the natural environment. Ambient temperature is a factor commonly recognized as having a significant impact on the start-up of an internal combustion engine. The analysis of the influence of temperature on the start-up of piston combustion engines concerns the mechanisms of its impact on the possibility of their starting [9]. Depending on ambient temperature, the starting process of a diesel passenger car engine may result in long cranking periods with a large amount of pollutant emissions [28 - 30] or in the complete incapability of starting the engine. Lowering the start-up temperature of the diesel engine causes a decrease in the angular velocity of the crankshaft, the battery's electrical capacity, deterioration of fuel atomization in the combustion chamber, increased thermal losses, increased friction force, etc., [9, 22, 31]. These problems are caused by poor conditions for auto-ignition: relatively low peak compression temperature and pressure [14].

2. METHODOLOGY

The test stand consists of a four-stroke direct injection single-cylinder engine by Ruggerini Diesel RY125. The RUGGERINI RY125 engine is a single-cylinder unit with a displacement of 505 cm^3 (85 mm stroke, 87 mm bore), is air-cooled, is capable of developing a rated power of 8.8 kW at 3600 rpm and has a maximum torque of 31 Nm at 2000 rpm [32], with valve system consisting of overhead 2 valves and compression ratio of 20:1. The test engine was equipped with a mechanical injection system with one-section injection pump, centrifugal speed controller, and mechanical injector with 5 holes. Scheme of the original test stand of a single-cylinder diesel engine is shown in Fig. 1. The tests of the parameters of the single-cylinder engine start-up process were carried out at an ambient temperature of 20 °C ± 2 °C, at the so-called engine cold start. The research was a series of 60 engine start-up tests samples. Testing tests were carried out without the use of devices supporting the start-up of the internal combustion engine. To ensure thermal equilibrium between the engine and its surroundings, cold start tests were carried out at the first daily start and after a fixed time from engine immobilization, i.e., at 4 hours. This is the time interval in which the engine reached a stable temperature condition from the previous start, i.e. a state in which all engine parts and operating fluids (engine oil) have the same temperature [33]. The engine start-up process is called from the button on control panel. All measurement signals were recorded using a DAQPad-607 (16imputs, 1.25MS/s, 12bit, Multifunction ±5V) measurement card from National Instruments.

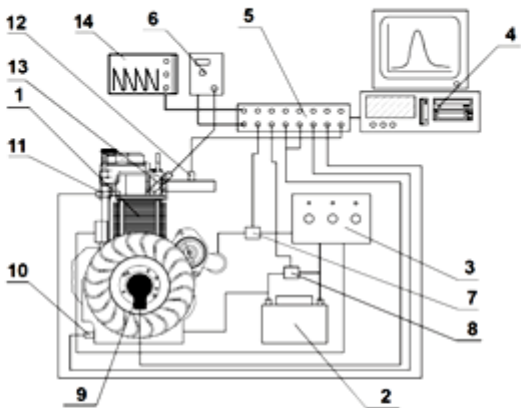

Fig. 1. The test stand scheme: 1 – engine, 2 – battery, 3 – control panel, 4 – measuring computer, 5 – measurement card, 6 – charge amplifier, 7 – starting current measurement system, 8 – voltage measurement system, 9 – encoder of crank angle, 10 – oil temperature sensor, 11 – cylinder temperature sensor, 12 – intake air temperature sensor, 13 – in-cylinder pressure sensor, 14 – reference voltage generator [33]

The tests were carried out at set fuel injection parameters such as the fuel injection advance angle of 16.6 degrees of crankshaft rotation and injector opening pressure of 21 MPa, with three different fuel doses (marked as 1, 2 and 3). The value of the fuel dose is defined as follows: 1 corresponds to idling engine operation, 2 corresponds to increased dose determined by constant shifting of the fuel dose control lever on the injection pump by 50% its regulation range, and 3 is a dose determined by constant shifting of the fuel dose control lever on the injection pump by 25% of its regulation range. In the Fig. 2 is a chart showing the values and parameters of the start-up process recorded during the test sample.

Umax is the maximum voltage value at the battery terminals measured just before the start of the engine. *Umin* is the minimum voltage value at the battery terminals measured at the beginning of the start-up. Imax is the maximum value of the current consumed by the starter at the beginning of the start-up, which is an indirect measure of the resistance to movement at the start of the engine. Starter operation time – *ts* – is the time elapsed from the moment the starter engage until the voltage and current reached a value corresponding to its unloaded operation.

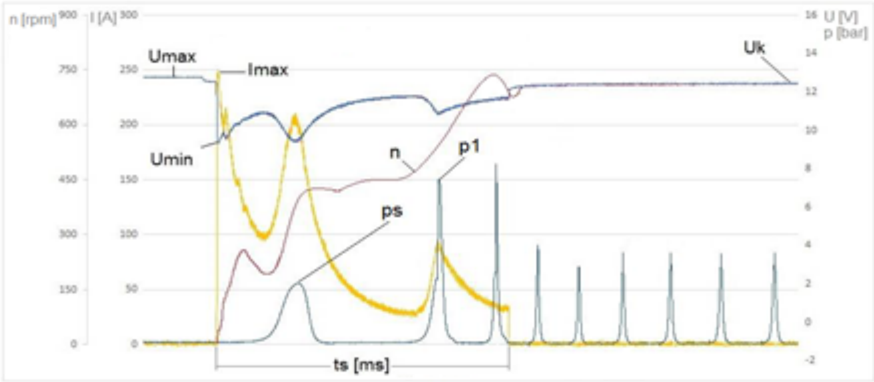

Fig. 2. Chart describing the recorded parameters of the start-up process: Umax – the maximum voltage before the start-up [V], Umin – the minimum voltage at the beginning of the start-up [V], Imax – the maximum current consumed by the starter at the beginning of the start-up [A], Uk – voltage at the end of data recording after the end of starting [V], n – engine speed [rpm], ps – compression pressure [bar], p1 – maximum pressures in the first combustion cycle [bar], ts – starter operation time [ms], [33]

Determination of the injector opening pressure was carried out in accordance with the recommendations included in the BN-84/1301-08 standard [34], on the PRW-3 injector test stand. The value of the fuel injection advance angle was determined by means of a stroboscopic lamp for setting the injection advance angle BOSCH ETD019.02 FD268 made by AVL. Tests were carried out in the laboratory of the Institute of Transport, Combustion Engines and Ecology at the Lublin University of Technology on its own research test stand.

3. TESTS RESULTS AND DISCUSSION

In the presented analysis, a comparison was made between the values of the start-up parameters (their changes) depending on the three fuel dose. In this study, the results of the following electrical start-up parameters were analyzed:

- the maximum current consumed by the starter,
- difference of voltages on the battery before and after the start-up,
- voltage drop on the battery at the beginning of the start-up,
- average power of the starter,
- starter operation time, and
- the maximum pressure value in the first combustion cycle.

Due to the failure to meet the assumptions of the classical analysis of variance, nonparametric Kruskal-Wallis test was used. Because this test is a median test, in order to better illustrate the effect of dose changes on the values of selected parameters, a regression analysis was used, which in turn takes into account changes in mean values. Due to the fact that the occurrence of even large individual values shifts the average value in their direction, it was decided to present the results in the form of minimum and maximum values (Fig. 3).

For the dependence of the maximum starting current on the fuel dose, the value of Kruskal-Wallis test is H = 2, N = 187, K-W = 0.2052089, with significance level p = 0.9025, which does not allow rejecting the zero hypothesis and indicates that the fuel dose has no significant effect on the value of the maximum starting current. As it results from the tests [31], this current depends mainly on the static friction values of the motor kinematic pairs at the moment of starting the start. Fig. 4 shows the linear regression of the maximum starting current from the fuel dose. The regression line equation and the correlation value R = 0.10641 were also marked. It also confirms the very weak dependence of the mean of the starting current on the fuel dose.

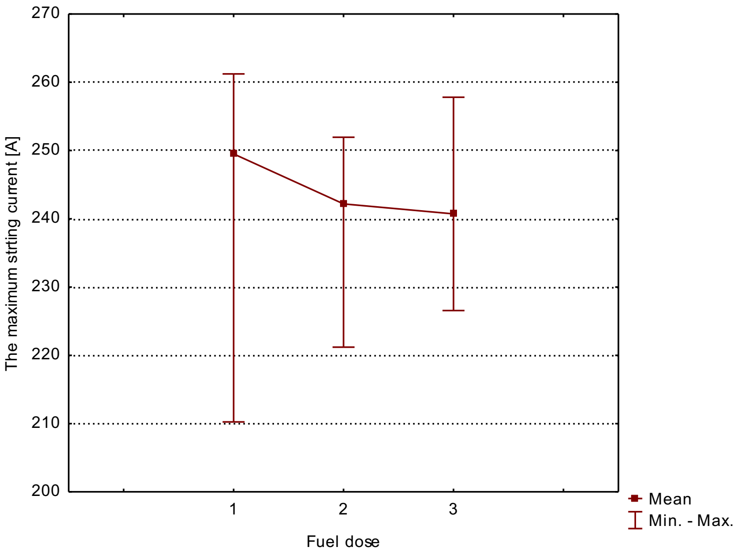

Fig. 3. The dependence of the maximum starting current on the fuel dose

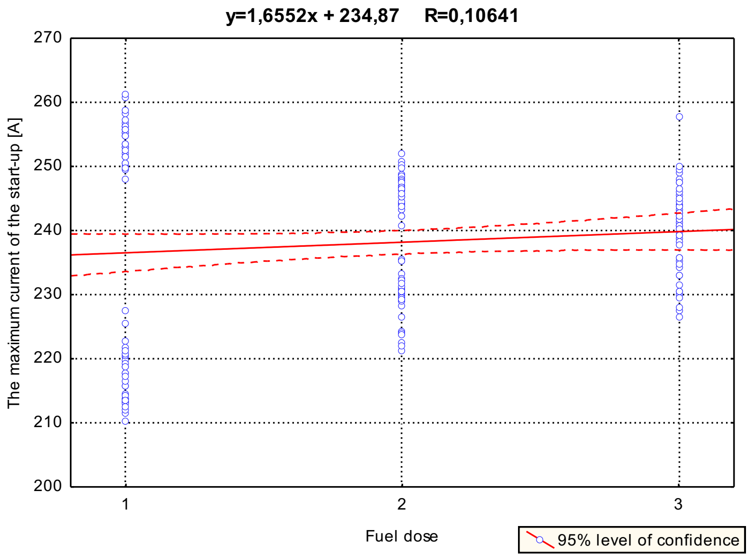

Fig. 4. Linear regression of changes in the maximum starting current concerning the fuel dose

Fig. 5 and 6 show the dependence of changes in the difference of voltages on the battery before and after the start-up of the fuel dose.

The value of the Kruskal-Wallis test is equal to H = 2, N = 187, K-W = 5.615403 for the dependence of the difference between the voltages on the battery before and after the start-up of the fuel dose, with the significance level p = 0.0603, which does not allow the rejection of the zero hypothesis and indicates the lack of statistically significant effect of the fuel dose on the value of difference of voltages on the battery before and after the start-up. In this case, the dependence of mean values of said difference voltage is also poor, as shown in Fig. 6 (correlation R = -0.1409).

Fig. 7 and 8 show the dependence of voltage drop on the battery at the beginning of the start-up concerning the fuel dose.

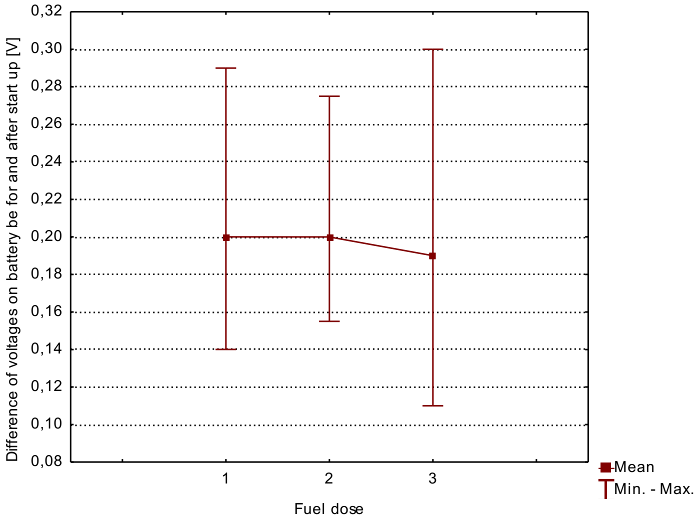

Fig. 5. The dependence of changes in the difference of voltages on the battery before and after the start-up of the fuel dose

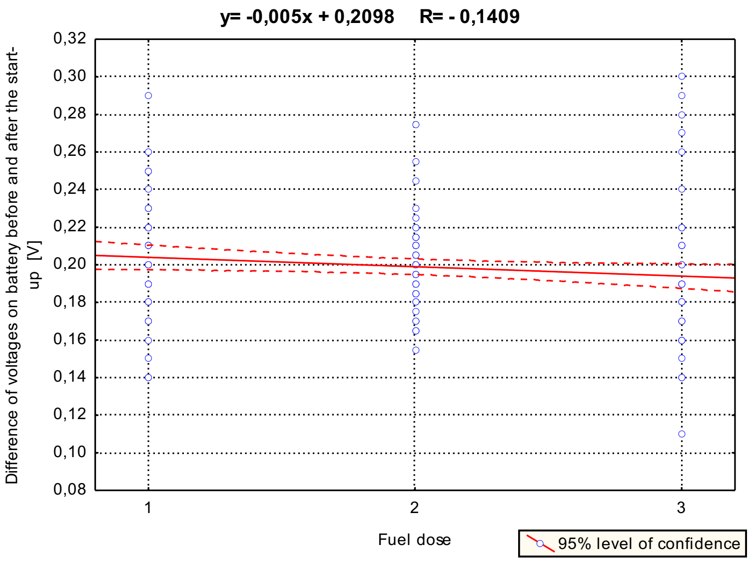

Fig. 6. Linear regression of changes in the difference of voltages on the battery before and after start-up concerning the fuel dose

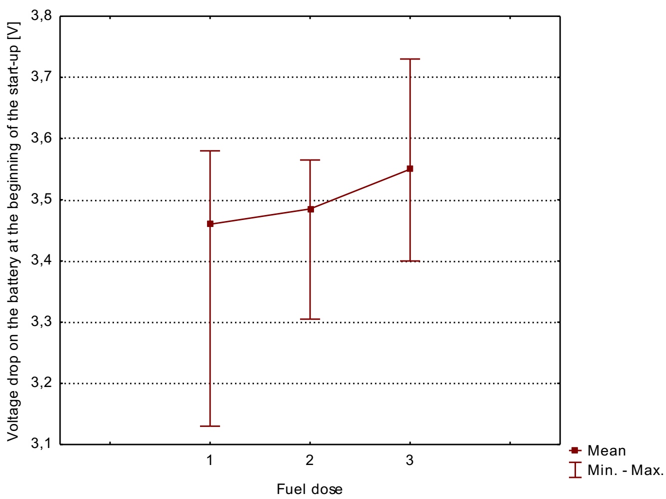

Fig. 7. The dependence of voltage drop on the battery at the beginning of the start-up concerning the fuel dose

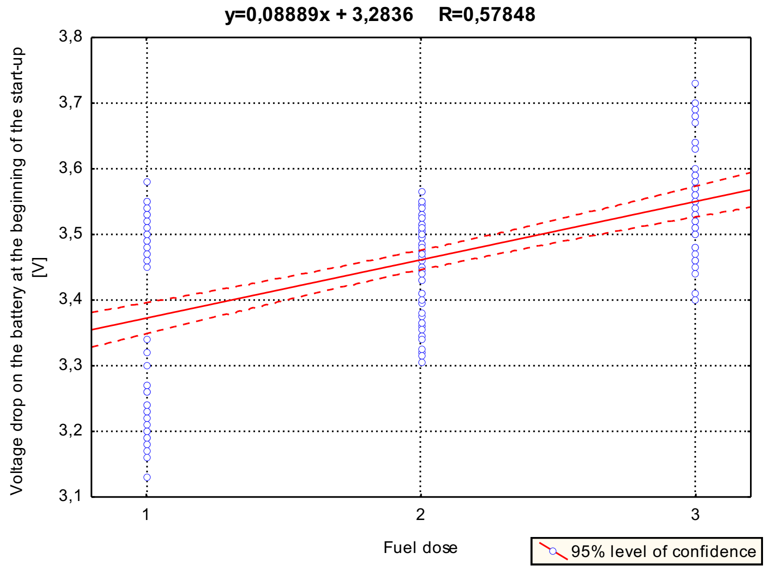

Fig. 8. Linear regression of voltage drop on the battery at the beginning of the start-up concerning the fuel dose

The value of the Kruskal-Wallis test is H = 2, N = 187, K-W = 55.80245 for the dependence of the voltage drop on the battery at the beginning of the start-up of the fuel dose, with the significance level p = 0.00001, which allows the rejection of the zero hypothesis. This indicates the existence of a significant effect of the fuel dose on the voltage drop on the battery at the beginning of the start-up. This correlation is also confirmed by the regression analysis presented in Fig. 8 (regression equation y = 0.08889x + 3.2836, correlation R = 0.57848). This means that increasing the fuel dose causes an increase in the amount of vaporized fuel, which increases the resistance to movement during the compression stroke.

Fig. 9 and 10 show the dependence of average power of the starter concerning the fuel dose.

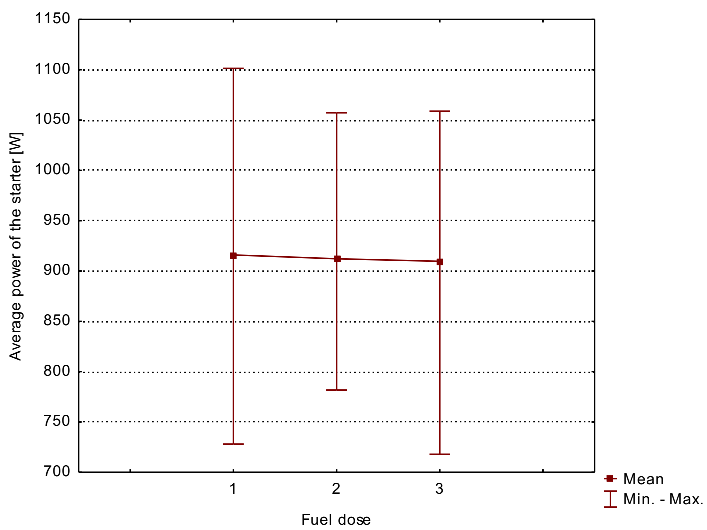

Fig. 9. The dependence of average power of the starter concerning the fuel dose

For the relation between the average power of the starter and the fuel dose, the value of Kruskal-Wallis test is H = 92, N = 187, K-W = 1.029614, with the confidence level p = 0.8621, which does not allow rejecting the zero hypothesis and indicates no significant effect of the fuel dose on the value of the average power of the starter. This is additionally confirmed by the very low correlation value R = -0.0894, (Fig. 10).

Fig. 11 and 12 show the dependence of starter operation time concerning the fuel dose.

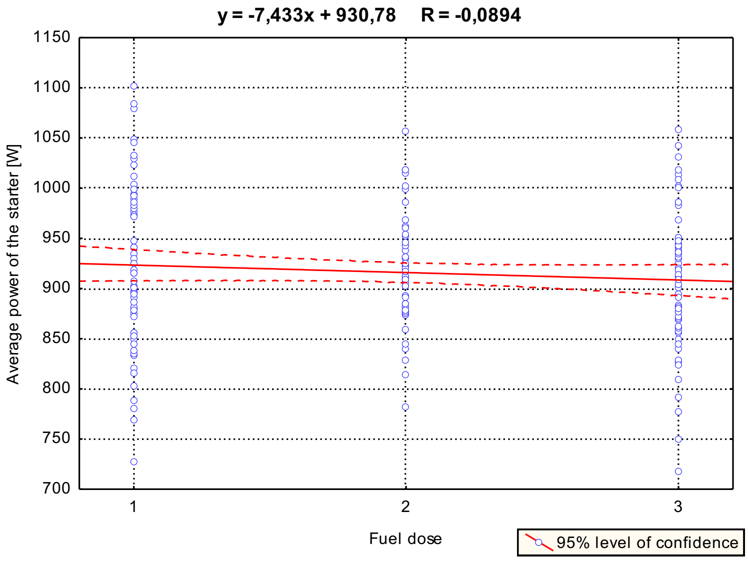

Fig. 10. Linear regression of average power of the starter concerning the fuel dose

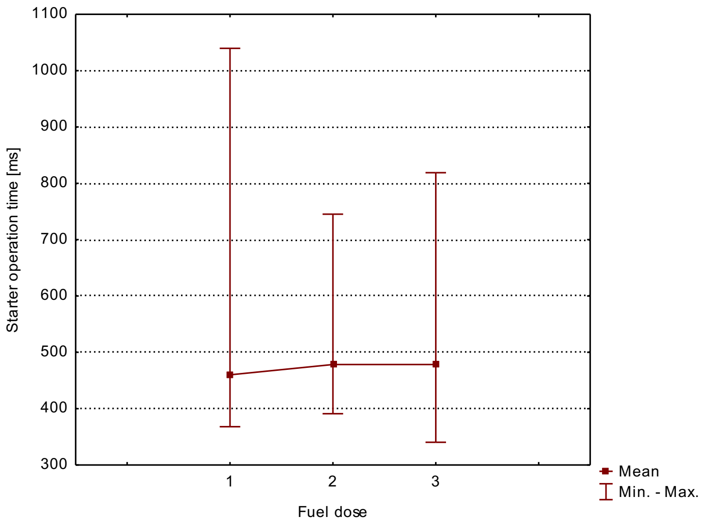

Fig. 11. The dependence of starter operation time concerning the fuel dose

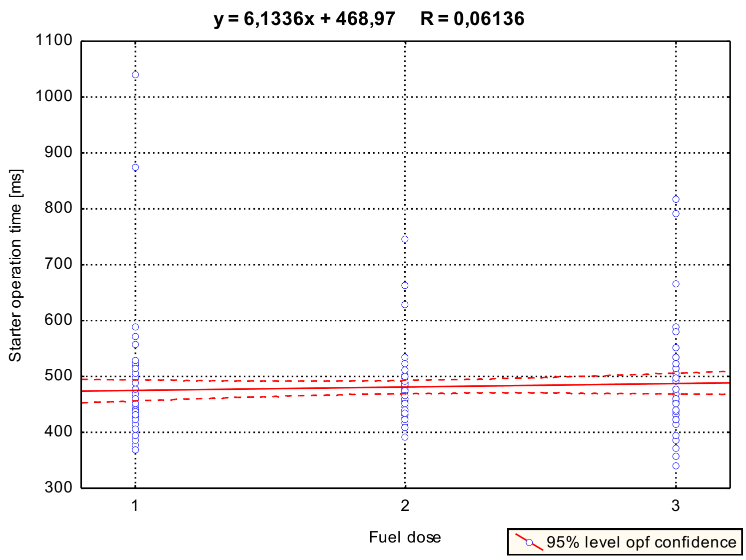

Fig. 12. Linear regression of the starter operation time concerning the fuel dose

For the dependence of the starter operation time value on the fuel dose, the Kruskal-Wallis test value is H = 2, N = 187, K-W = 3.777374, with a confidence level p = 0.1513, which does not allow rejecting the zero hypothesis and indicates no impact of the fuel dose on the starter operation time. This further confirms the very poor correlation, with R = 0.06136, (Fig. 12).

Fig. 13 and 14 show the dependence of the maximum pressure value in the first combustion cycle concerning the fuel dose.

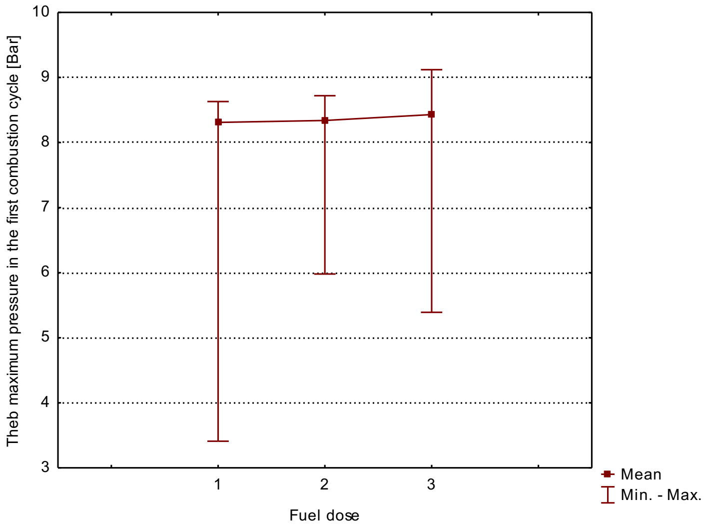

Fig. 13. The dependence of the maximum pressure value in the first combustion cycle on the fuel dose

For the dependence of the maximum pressure value in the first combustion cycle on the fuel dose, the Kruskal-Wallis test value is H = 2, N = 187, K-W = 1.543726, with a confidence level p = 0.0004, which allows the rejection of the zero hypothesis and testifies to the existence of the effect of the fuel dose on the value of the maximum pressure of the first combustion cycle.

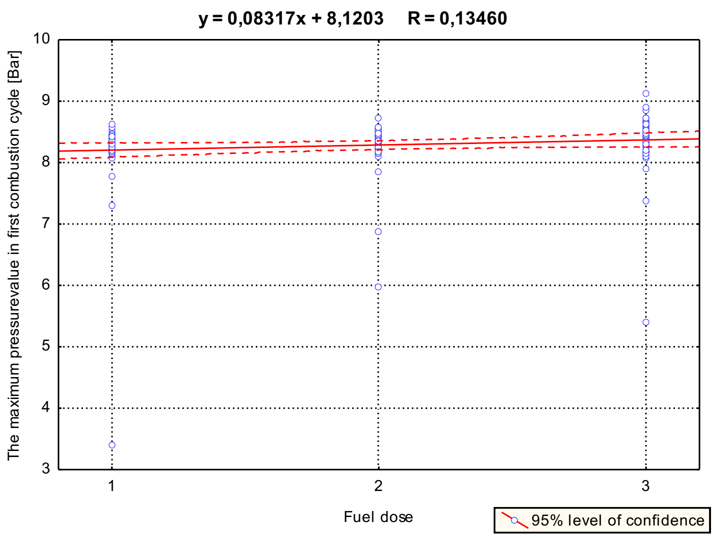

Fig. 14. Linear regression of the maximum pressure value in the first combustion cycle on the fuel dose

Comparison of Fig. 13 and 14 shows that the distributions of maximum pressure value in the first combustion cycle have similar media and average values, which indicates a high concentration of results. The existing effect of the dose on the value of the maximum pressure value of the first combustion cycle can be explained similarly to the increase in voltage drop on the battery at the beginning of the start-up. An increased fuel dose causes an increase in the amount of vaporized fuel which translates into an increase in resistance during the compression stroke and an increase in the amount of fuel burned - which results in a higher pressure in the first cycle of the engine's operation. This increase is statistically significant, although not too high, as evidenced by the direction coefficient of the regression equation ($y = 0.08317x + 8.1203$) and the correlation value ($R = 0.13460$).

4. CONCLUSIONS

The article presents the impact of the fuel dose on the results of tests of selected starting parameters of a single-cylinder diesel engine. There is a statistically significant effect of the fuel dose on the value of parameters, such as voltage drop on the battery at the beginning of the start-up and maximum pressure value in the first combustion cycle.

The observed effect can be explained by the course of physical and chemical processes occurring during engine start-up, including the increase in the amount of vaporized and then burnt fuel (due to the increase in the fuel dose).

For the remaining parameters analyzed (the maximum starting current, the difference of voltages on the battery before and after start-up, the average power, and the starter's operating time), there was no statistically significant dependence on the fuel dose size. This is owing to their randomness. For example, the value of the maximum starting current in addition to the fuel dose is also influenced by the static friction value of the kinematic pairs of the engine at the moment of starting the start-up. This results in a large dispersion of the obtained values. The medians of the obtained distributions have a decreasing characteristic, and the average values are increasing, as evidenced by the correlation coefficient and the regression line. With the increase of the fuel dose, the increase of the maximum starting current is also observed.

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