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Laboratory Tests of Electrical Parameters of the Start-Up Process of Single-Cylinder Diesel Engines

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Abstract: Despite continuous work on new power systems for vehicles, machines, and devices, the combustion engine is still the dominant system. The operation of the combustion engine is initiated during the starting process using starting devices. The most common starting system used is the electric starter. The starting process of an internal combustion engine depends on the following factors: the technical condition of the starting system, technical condition of the engine, battery charge level, lubricating properties, engine standstill time, engine and ambient temperature, type of fuel, etc. This article presents the results of laboratory tests of the electrical parameters of the starting process of a single-cylinder compression–ignition engine with variable fuel injection parameters and ambient temperature conditions. It was confirmed that for the increased fuel dose FD2, higher values of the measured electrical parameters (*Imax*, *Pmax*, and *Pmed*) were obtained compared to the series of tests with the nominal fuel dose. Knowledge of the values of the electrical parameters of the starting process is important not only for the user (vehicle driver, agricultural machinery operator, etc.), but above all for designers of modern starting systems for combustion engines and service personnel. The obtained results of testing the electrical parameters of the combustion engine during start-up may be helpful in designing new drive systems supported by a compression–ignition combustion engine.

Keywords: electrical current consumption; electric starter; technical condition; combustion engine

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1. Introduction

Despite continuous scientific and research work on new power systems for vehicles, machines and devices, the combustion engine is still the dominant system. The internal combustion engine is practically irreplaceable in the case of large self-propelled agricultural machines such as combines and agricultural tractors that can work without interruption during the field work season. It is true that in the case of agricultural tractors there are attempts to replace tractors powered by combustion engines with electric drives [1–3], but these are rather marginal applications inside small farms or orchards [4,5].

The diesel engine is currently the most common source of propulsion for road transport, both in the classic system and in the hybrid system, supporting the electric motor. Research on hybrid systems used to drive motor vehicles is widely described in the available scientific literature, of which the following studies are worth mentioning [6–8]. According to the 2023 report presented by the ACEA European Automobile Manufacturers Association [9], the share of passenger cars powered by diesel engines in 2021 was 41.9%. In the case of small delivery vehicles with a load capacity of up to 3.5 tons, it was almost 91%, while the share of medium and heavy trucks was 96.4%, and in the case of buses, it was 92.5% of the vehicle market.

A compression ignition engine has advantages such as reliability, fuel efficiency, larger power range, longer lifetime and maintenance period, better torque characteristics, and higher power density compared to a spark ignition engine [10]. The diesel engine is the most fuel-efficient internal combustion engine; however, the performance of a diesel engine is suboptimal when the engine is cold [11]. Modern piston engines must be characterized by high operating efficiency and the lowest possible production of exhaust gases and noise [12,13]. Also, noise generation from compression ignition engines is a widely discussed problem in the literature [14–16], and noise emissions from various means of transport [17–19]. Smoke and noise emission reduction from an internal combustion engine with the addition of ferocene were tested by Sejkorova et al. [15], but they did not demonstrate a positive effect of using this fuel conditioner. Verner and Sejkorova [20] conducted research comparing the results of carbon dioxide (CO_2) emission measurements of passenger cars powered by diesel and gasoline engines obtained with PEMS and CVS measurement systems in laboratory conditions on a dynamometer, in accordance with the WLTC driving cycle methodology. The results show that there are no statistically significant differences between CVS and PEMS devices, which are typically used to measure real driving emissions (RDE) [20]. The issues of examining the composition of exhaust emissions from a compression–ignition engine are widely discussed in the world literature [21–23] and also include studies of exhaust emissions generated during engine start-up [24–26]. Currently, most research focuses on, among other things, exhaust emissions generated during the combustion of alternative fuels to diesel oil. As we know, the first designs of diesel engines were fueled by vegetable oil [27]. In this area, it is worth mentioning the following scientific and research works: Ding et al. [28] investigated the use of natural gas in a diesel engine, Longwic and Sander [29] extensively studied mixtures of rapeseed oil containing n-hexane, and Labaj and Barta [30] investigated the possibility of using butanol in a diesel engine. Numerous scientific works focus on the study of biodiesel and its impact on exhaust emissions, including [31–35]. In research carried out by Imran and Saleh [36], it was shown that biodiesel from Cresson oil and mixtures with Iraqi diesel oil reduce engine thermal efficiency and heat release, as well as delay time and cylinder pressure, while exhaust gas temperature and fuel consumption during braking increase. In the case of emissions, an increase in the share of nitrogen oxides (NOx) and CO_2 was recorded, while the emission of carbon monoxide (CO), soot, and unburned hydrocarbons (HC) looked favorable with their decreased values. Ramalingam et al. [37] investigated the possibilities of obtaining bioenergy from waste foam fat (LFO) and citronella grass (NFCO). Compared to diesel, the NFCO blend reduced HC, CO, and particulate matter (PM) emissions by 6.48%, 12.33%, and 16.66%, respectively, while CO_2 and NOx emissions increased [37]. As stated by Szyszlak-Bargłowicz et al. [38], the combustion of FAME rapeseed oil methyl esters resulted in a reduction in PM content in exhaust gases by an average of 40–60% for engine speeds in the full-load range compared to that from the combustion of diesel oil. We can say that biodiesel for use in diesel engines has become a substitute for diesel oil [39]. Furthermore, Dittrich et al. [40] studied the fuel control system when an engine uses LPG–diesel dual fuel with different LPG proportions. They concluded that CO_2 and PM concentrations are reduced in dual-fuel vehicles. Interesting research on alternative fuels in dual-fuel diesel engines was also conducted by Cung et al. [41] and Lebedevas et al. [42]. Basically, exhaust emission tests come down to determining the values of four standard exhaust gas components, but there are researchers, e.g., Mikulski et al. [43], who use FTIR analysis of exhaust gases where they identify 23 exhaust gas compounds. In order to make heating systems more efficient and to better understand electricity generation, a number of studies have been carried out, of which the following are worth mentioning [44–46]. An important area of research when it comes to reducing emissions is also the adsorption and regeneration of the system, which includes the coupling of physical and chemical effects [47]. Based on the above considerations, it can be concluded that the issue of emissions is a complex issue in the field of combustion engine research and depends on many factors. One of them is the emission of exhaust gases during the starting process, where a larger dose of fuel is needed to initiate the operation of a cold engine, and the exhaust gas treatment systems with which the engine is equipped are not yet operational. In such conditions, at the beginning of engine operation, there are increased exhaust emissions into the atmosphere. Therefore, the issue of starting a combustion engine is still a current issue and is constantly being addressed by scientists around the world. And new challenges leading to "zero emission" are becoming a current challenge for combustion engines.

As is known, the combustion engine must ensure reliable operation for a very long time [48–51] under variable load conditions. Interesting operational tests of the diesel engine power system were carried out, among others: Aulin et al. [52], Kamiński et al. [53], Osipowicz et al. [54], and Punov et al. [55]. Pawlak and Skrzek [56] also modified the injection strategy in the Common Rail system using vegetable oils. Stoeck [57] presented a new methodology for testing Common Rail injectors in problematic cases, which extends the standard diagnostic procedure by analyzing the resultant fields of the dosed fuel. Moreover, much attention was paid to the issue of diagnosing faults in the fuel supply system in the following scientific studies by Figlus et al. [58,59] and Szpica et al. [60] and to the wear of the cylinder liner during the start-up of a compression–ignition engine [61,62]. The operational wear and durability of the piston–rings–cylinder system was investigated by Czech and Madej [63] and Kowalski et al. [64], the wear of the crankshaft of a marine engine was the subject of research by Siemiątkowski et al. [65], while measurements of engine cylinder wear were presented by Jermak et al. [66]. Another study on measuring diameter uncertainty and roundness deviation for small cylinders was presented by Zhao et al. [67].

The process of starting a diesel engine, despite many years of research, is a phenomenon that still attracts the attention of many researchers, which is reflected in numerous scientific works [59,68,69]. Many works are related to starting the engine in conditions of low ambient temperatures, for example, those of Chu-Van et al. [70], Deng et al. [71], Pastor et al. [72], and Roberts et al. [73]. Similarly, a lot of research work has been carried out under hot start conditions, for example, Jaworski et al. [74], Lodi et al. [75], Mitchell et al. [76], and Zare et al. [77]. When starting a diesel engine, many negative phenomena and processes are observed that affect not only the engine, but also its surroundings [78,79]. For example, Droździel, in [80], presents the results of tests of the operational electrical parameters of the start-up of the combustion engine, carried out during vehicle operation. The starting process is influenced by many factors, such as the quality of the engine oil, battery charge, technical condition of the engine and starting system, and engine temperature. The starting process also depends on various settings and strategies as well as the condition of the engine's injection system [78,81,82]. The necessary mechanical energy needed to initiate independent operation of the combustion engine is transferred by driving the crankshaft using an electric starter [80]. Therefore, the technical condition of the starter has a significant impact on the successful starting of the combustion engine. The issue of car electric starters, in detail, are presented in the works by Dziubiński et al. [83,84] and Plizga [85].

Despite many attempts, replacing the combustion engine with another yet equally efficient drive source is still a long way off. Despite huge progress in the field of individual electromobility [86–90] and in the field of public transport [91,92], they still encounter many barriers [93,94], and space for piston engines is still huge. The opening of new research directions in the field of alternative fuels used for transport modes, such as hydrogen [95–98] or ammonia [99–101], for powering internal combustion piston engines in various means of transport pose new challenges for internal combustion engines. Also, in non-road applications, there is an important share of single-cylinder combustion engines [102].

This article presents selected results of laboratory tests on the electrical parameters of the start-up of a single-cylinder diesel engine at constant injector opening pressure and fuel injection advance angle for two fuel doses at ambient temperature. Experimental tests were carried out on a dedicated laboratory test stand at the Lublin University of Technology.

2. Materials and Methods

The main elements of the test stand are a single-cylinder, four-stroke engine with direct fuel injection Ruggerini Diesel RY125 manufactured by Lombardini, Italy, a control and data recording system, as well as a starting and exhaust gas discharge system. Table 1 contains selected technical data of the research engine and its starter. The starting system installation voltage is nominally 12 V, the battery's electrical capacity is 60 Ah, and the maximum starting current is 570 A. The starting battery was well charged during the research tests.

Table 1. Ruggerini RY125 series engine technical specification [103].

Parameter	Type/Value
Type of cooling	Air
Displacement	505 cm^3
Power	8.8 kW at 3600 rpm
Maximum torque	31 Nm at 2000 rpm
Number of valves	2
Compression ratio	20:1
Cylinder diameter	87 mm
Piston stroke	85 mm
Number of injector holes	5
Starter voltage	12 V (Bosch 0 001 107 090)
Rated power of starter	1.1 kW
Maximum rotational speed	300 rpm
Direction of rotation	Right
Number of pinion teeth	11

The test stand (Figure 1) is equipped with equipment for measuring the characteristic parameters of the diesel engine start-up process. On the test stand, information about the position of the engine crankshaft was obtained from the Kübler incremental encoder 8.5820.1312.3600 (Kübler Group, Fritz Kübler GmbH, Villingen-Schwenningen, Germany). TP-371, TP-372 sensors with a single processing element (Pt100 platinum resistor) were used to measure cylinder temperature, oil temperature and ambient temperature. The current drawn by the starter was measured by a LEM sensor, HTA-1000, attached to the starter power cord. The sensor measures currents in the range of 0 ÷ 1000 A with an accuracy of ±1% and linearity of ±0.5%. It is equipped with a voltage output of 0 ÷ 4 V and a frequency response of 40 kHz. The voltage at the battery terminals was measured using a specially made measuring system based on two 100 Ω resistors connected in series [78]. All measurement signals were recorded using the National Instruments measurement card DAQPad-6070E (16 imputs, 1.25 MS/s, 12 bit, multifunction ± 5 V).

The tests of the electrical parameters of the start-up process of the diesel engine were carried out on the so-called cold engine. Cold starts of the engine took place at the first daily start-up and after a set time from the engine standstill, at 4-h intervals, with the determined fuel injection parameters and at the ambient temperature. A total of 30 attempts were made to start the engine in a given test series. The starting tests were carried out with the following determined engine parameters:

- Static fuel injection advance angle—17.6 °CA;
- Injector opening pressure—26 MPa;
- Fuel dose—factory default for idling—FD1, and increased—FD2;
- Idle speed—810 rpm for fuel dose FD1 and 1000 rpm for fuel dose FD2;
- Start-up temperature—in the range of 22.75–23.95 °C.

There are multiple definitions of an engine cold start or engine warm up found in the literature [70,75,104]. In the literature on the subject, there are many possibilities in evaluating the parameter of start-up time. In these tests, the start-up time was determined based on the moment a stable rotational speed of the engine crankshaft was obtained.

On the other hand, the starter operation time was determined on the basis of energy consumption time at the battery terminals. The parameter *ts* is the starter operating time [ms], understood as the time that elapses from the moment the starter is turned on until it reaches unloaded operation. *Imax* is the maximum value of the current consumed by the starter at the beginning of the start-up [A], which is an indirect measure of the resistance to movement at the start of the engine. The *Umax* parameter describes the maximum voltage value measured at the battery terminals just before the engine start-up process [V]. *Umin* describes the minimum voltage at the beginning of the start-up [V], *Uk* describes the voltage at the end of data recording after the start-up [V], and *n* is the engine speed [rpm]. In Figure 2 is a chart showing the values and parameters of the start-up process recorded during the test sample.

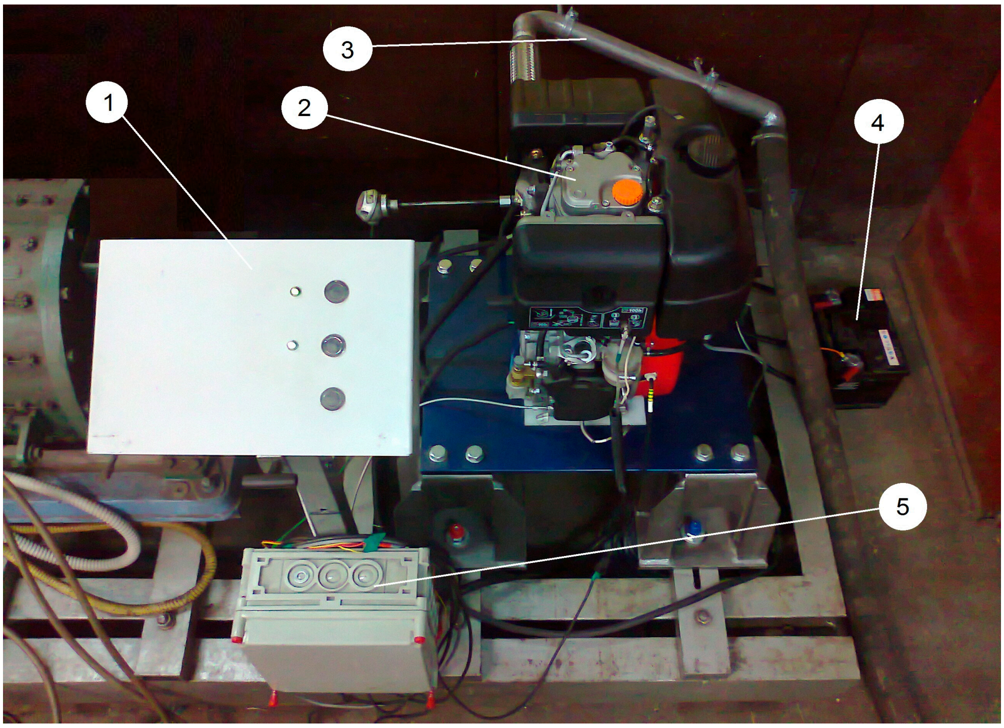

Figure 1. View of the research stand: 1—control panel, 2—research engine, 3—exhaust gas discharge system, 4—starting battery, 5—connection of measurement signals [78].

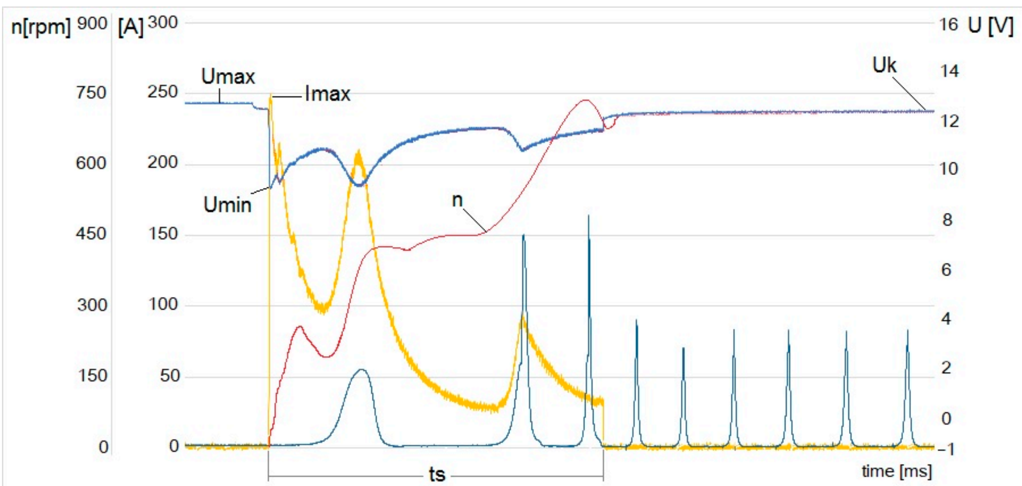

Figure 2. Chart describing the recorded parameters of the start-up process.

Determination of the injector opening pressure was carried out in accordance with the recommendations included in the BN-84/1301-08 standard [105], on the PRW-3 injector test stand. The value of the fuel injection advance angle was determined by means of a stroboscopic lamp ETD019.02 FD268, BOSCH, Germany.

3. Results and Discussion

This part presents the obtained test results for the following start-up parameters: the maximum current consumed by the starter at the beginning of the start-up—*Imax*, the minimum voltage at the beginning of the start-up—*Umin*, maximum instantaneous starting power—*Pmax*, average starting power—*Pmed*, and starter operating time—*ts*. Start-up tests were carried out at ambient temperature, which is widely used in the literature [26,79,106]. The value of the injector opening pressure in both measurement series was 26 MPa. The tests were carried out with two fuel doses: a nominal fuel dose marked as FD1 and an increased fuel dose marked as FD2.

Figure 3 presents the distribution of the values of the maximum current consumed by the starter at the beginning of the start-up for the two measurement series.

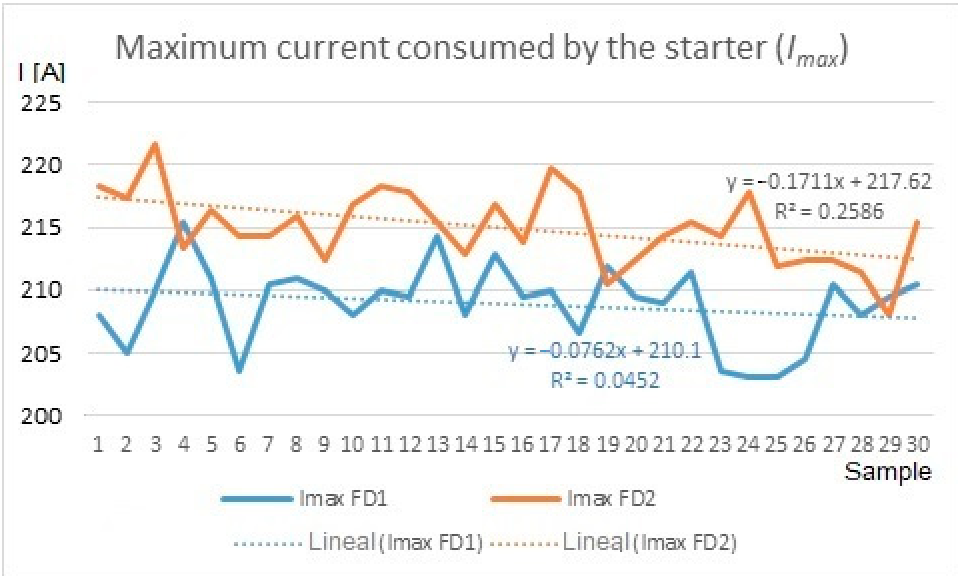

Figure 3. Values of the maximum current consumed by the starter for two measurement series.

As can be seen in Figure 3, the current value is usually lower for starting attempts in the first measurement series, i.e., at the nominal fuel dose, FD1. In the case of most recorded starting attempts, the difference between the series is small, approximately 7 A, and this is the average value of this parameter. Both series of experiments were performed at a similar ambient temperature of approximately 23 °C. As one can see, increasing the fuel dose requires more effort, and therefore, the maximum value of the current consumed during starting is higher in this case. It can therefore be said that with these starting parameters and a given ambient (engine) temperature, increasing the fuel dose results in a greater demand for electricity.

Figure 4 shows the distribution of minimum voltage values at the battery terminals at the beginning of the start-up for the two measurement series.

Analyzing the graph in Figure 4, it can be seen that in the case of the second test series, i.e., the test with an increased dose of FD2 fuel, lower values of voltage drops on the starter battery were obtained. This indicates that a larger amount of fuel in the combustion chamber places a greater load on the starter battery. It should also be noted that in most cases, very similar voltage values were obtained, and the voltage course is basically undisturbed. And looking at the trend lines, they run similarly in both measurement series, which is also confirmed by the correlation coefficient R^2.

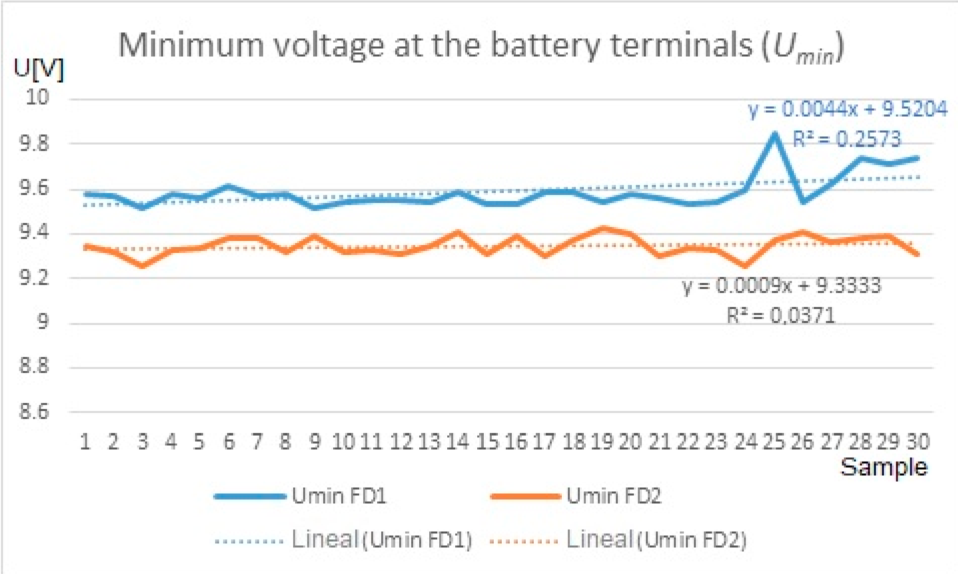

Figure 4. Minimum voltage at the battery terminals at start-up for two measurement series.

Figure 5 presents the distribution of the maximum value of the instantaneous starting power, *Pmax*.

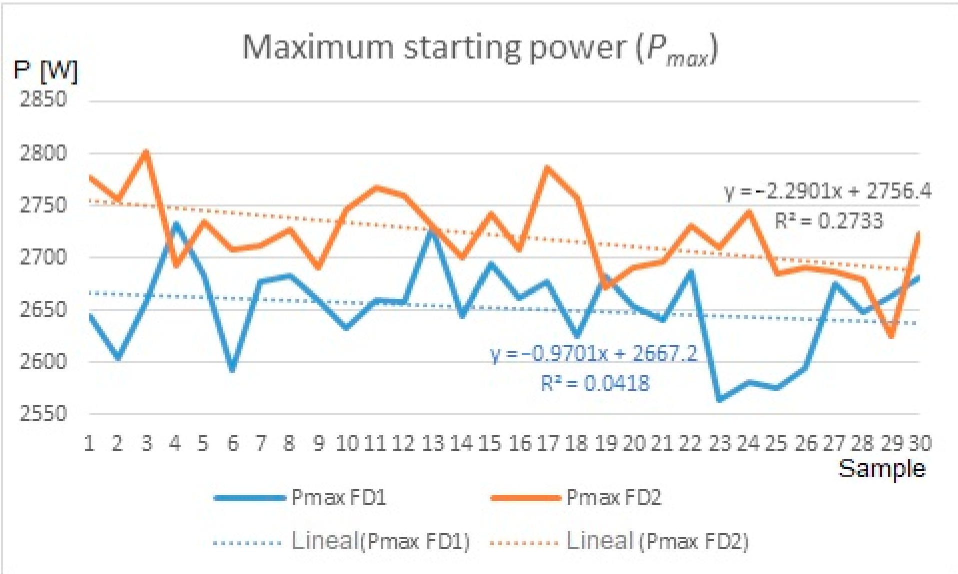

Figure 5. Maximum instantaneous starting power for two measurement series.

Analyzing the course of the parameters in the graph in Figure 5, it can be seen that in the case of an increased dose of FD2 fuel (second series), higher values of the maximum starting power occurred, which confirms the obtained values of the previously analyzed electrical start-up parameters.

Figure 6 presents the distribution of average starting power values *Pmed* for two measurement series.

Analyzing the course of the graph in Figure 6, it is difficult to notice the dominant tendency, but based on empirical data, it can be said that the average starting power *Pmed* is higher for a series of starts with the larger fuel dose FD2. This means that in the case of an increased fuel dose in these ambient conditions (average starting temperature of 23 °C), the growth of fuel in the combustion chamber causes a greater demand for electrical power, i.e., the starter must perform more work than in the case of starting the engine with the nominal fuel dose. It should be remembered that temperature has a significant impact on the start-up process of combustion engines, which is confirmed by numerous publications [71,79,106,107].

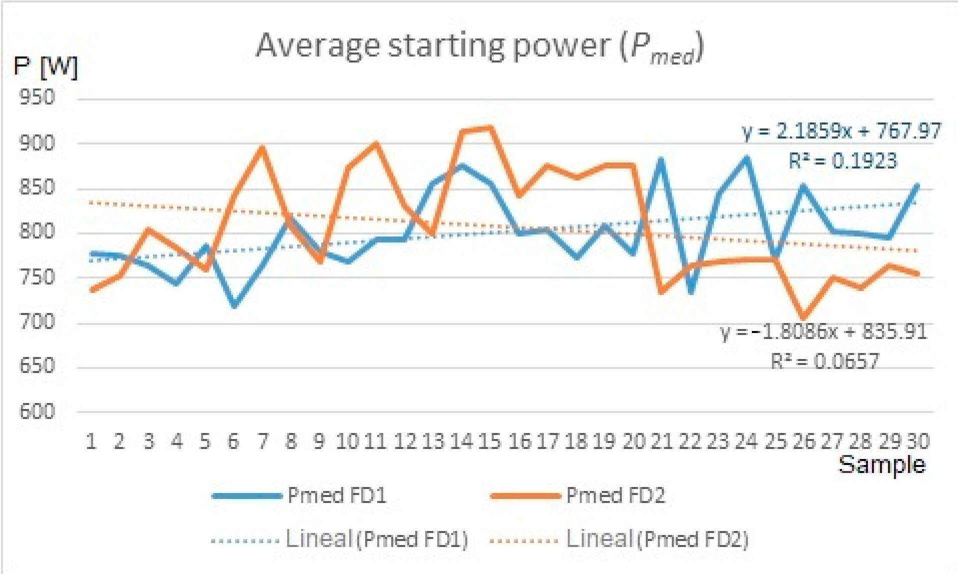

Figure 6. Average starting power *Pmed* for two measurement series.

Figure 7 shows the values of the starter operating times in each series of tests, expressed in milliseconds ([ms]).

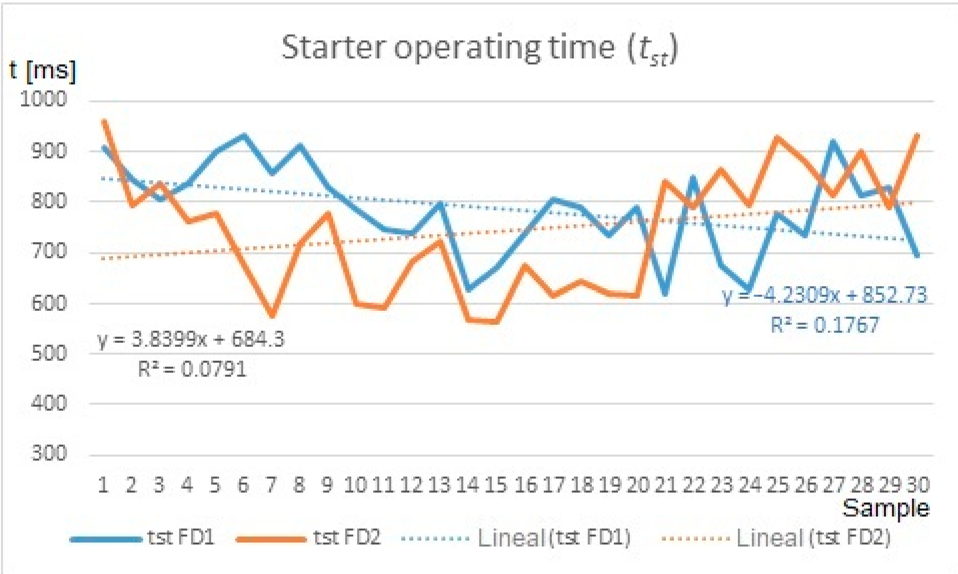

Figure 7. Starter operating time for two measurement series.

If we look at the trend line in the case of the starter operation time (Figure 7), we can see that the second series with an increased fuel dose, FD2, needed more time to start the engine than in the series with a nominal fuel dose, FD1; i.e., as already stated above, the starter performed a greater work. However, in the case of these two test series of starting tests of the diesel engine, the starter operating times, and therefore the engine start-up time, do not show any major differences. It can therefore be said that with the assumed starting parameters, fuel supply system, and given ambient temperatures, the starter operating time shows similar empirical values. For comparison, the values of the starter operating time when trying to start the engine can be quoted. Thus, for series 1 (with FD1), the shortest starter operating time was 621.6 ms, while the longest time was 932.4 ms. In the case of test series 2, the shortest starter operating time was 562.4 ms, while the longest starter operating time in this series was 962 ms. Therefore, it can be said that the start-up time is random and independent of the settings of the engine control parameters, which is also visible in the interpenetration of the trend lines of both measurement series. The presented values also indicate slight differences in start-up times between the compared test series. Moreover, it can be concluded that a higher fuel dose means a larger amount of fuel–air mixture inside the cylinder, i.e., in the combustion chamber. Compressing a larger volume of refrigerant causes greater resistance to piston movement and the starting system must overcome the additional load, providing greater engine torque, which is also visible in a higher value of starting current (*Imax*).

The presented research results may be helpful in designing starting systems for compression–ignition combustion engines and may be a contribution to simulation studies in this area. Scientists are still very interested in the process of starting an internal combustion engine [108,109] and new applications. For example, Coronado et al. [110] investigated the availability of cogeneration systems in extreme areas (Antarctica) for a waste heat recovery system with a diesel generator using a continuous Markov approach and a Markov state space model.

4. Conclusions

This paper presents the new results of experimental tests of the electrical parameters of the start-up process of a single-cylinder diesel engine with variable fuel injection parameters under positive ambient temperature conditions (approximately 23 °C). Experimental tests were carried out for an engine powered by diesel oil with a 5% share of so-called eco-additives, but the next steps will be testing the emissions of the internal combustion engine during start-up and testing alternative fuel use.

This research on the starting process of a combustion engine was carried out at a constant injector opening pressure of 26 MPa with the variable fuel doses FD1 and FD2. It was shown that in the case of an increased fuel dose, FD2 (second test series), higher values of measured electrical parameters (*Imax*, *Pmax*, and *Pmed*) were obtained compared to the test series with the nominal fuel dose marked as FD1. However, in the case of starter operation time, slightly shorter starting times were achieved for series 1 compared to series 2 with an increased fuel dose. It can therefore be summarized that with the given fuel injection parameters and given positive ambient temperatures (approximately 23 °C), starting attempts carried out with an increased fuel dose are unfavorable because they resulted in higher current consumption, i.e., they placed a greater load on the starter battery as well as the starter, which worked with greater power.

In this study, the influence of ambient temperature did not have a major impact on start-up success because the ambient temperature range was very similar, approximately 23 °C, which did not significantly affect the experiments performed. The presented results of research on the electrical parameters of the combustion engine in the start-up process may be helpful in configuring other drive systems supported by the internal combustion engine. These systems do not have to be limited only to powering motor vehicles or stationary systems for generating electricity; they may be important for service technicians or for designing new agricultural machines or off-road mobile machinery using internal combustion engines.

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Data Availability Statement: Data are contained within this article.

Conflicts of Interest: The authors declare no conflicts of interest.

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