

Analysis of the Influence of Fuel Dose on the Electrical Parameters of the Starting Process of a Single-Cylinder Diesel Engine

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ABSTRACT

The start-up is a transient state of operation of a compression-ignition engine during which many negative phenomena occur that affect the technical condition of the engine and its electrical devices and the surroundings. The start-up process of an compression-ignition engine is influenced by many factors, such as: technical condition of the starting system, technical condition of the engine, battery charge level, lubricant properties, engine standstill time, temperature of the engine, etc. Mechanical energy is required to start the engine, supplied by an electric starter by drives the engine's crankshaft. The paper presents the results of experimental tests of electrical parameters of the single-cylinder diesel engine start-up process at variable fuel injection parameters under ambient temperature conditions. Higher values of the measured electrical parameters (I_{max} , U_{min} , P_{max} , P_{med}) were obtained for the nominal FD1 fuel dose, compared to the tests with an increased FD2 fuel dose. Knowledge about the operating parameters of the electric starter during the start-up process is important for the engine user (vehicle driver) and of course for designers of modern combustion engine starting systems as well as service personnel.

Keywords: electricity consumption; electric starter; technical condition; diesel engine.

INTRODUCTION

The compression-ignition engine is currently the most common source of propulsion for means of road transport, both in the classic system and in the hybrid system, supporting the electric motor. In the literature, one can find numerous scientific papers on the study of hybrid systems in motor vehicles, such as: [1, 2, 3, 4]. According to the report from 2021 [5] of the European Automobile Manufacturers Association, in 2019 the share of

passenger cars with compression-ignition engine was 42.3%. In turn, in the case of small delivery vehicles up to 3.5 tons, it accounts for almost 90%, medium and heavy trucks account for 97.8%, and the share of buses is 94.5% of the market.

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 [6]. The compression-ignition engine

is currently the most fuel-efficient internal combustion engine, but its performance is suboptimal when the engine is still cold [7]. The compression-ignition piston engines used today must be able to generate as little harmful environmental effects as possible, which means that they must produce low exhaust and noise emissions [8]. Many scientific works [9, 10, 11] have been devoted to the issue of exhaust gas emissions from the operation of compression-ignition engines, including gas emissions under laboratory conditions [12, 13], as well as during engine start-up [14, 15, 16], which confirms the relevance of this problem. One way to reduce exhaust emissions is to look for alternative fuels to diesel fuel. Labaj and Barta [17] investigated the butanol application for diesel engine. In this context, it is worth mentioning the following scientific research works: Ding et al. [18] who studied the applications of Natural Gas, Longwic and his team [19] who studied rapeseed oil mixtures containing n-hexane, Domański et al., [20] who investigated selected biofuels, crop-based fuels [21], biodiesel from *Jatropha curcas* oil [22], camelina-based biofuel was studied by Lebedevas et al., [23] and diesel fuel and FAEE blends were presented in [24]. However, Dittrich et al., [25] conducted an investigation of the fuel control system when the engine uses a dual-fuel LPG-Diesel mixture with different LPG proportions. They concluded that the concentration of CO₂ and particle concentration are decreased in dual fuel. Interesting research on alternative fuels in dual-fuel diesel engines was also conducted by Cung [26] and Lebedevas [27]. Also, noise generation from compression ignition engines [28, 29], or noise emissions from various means of transport, for example train [30], motorcycle [31], passenger car [32] moving vehicles [33], and from traffic [34, 35] is a widely discussed problem in the literature. In addition, it is required that the combustion engine ensures reliable operation over a very long period of time [36, 37, 38] under variable load conditions [39]. The operational tests of the diesel engine power supply system with diesel engine were carried out, among others [40, 41, 42, 43, 44]. The modification of the injection strategy in the common rail system was also studied by Pawlak and Skrzek [45] when using vegetable oils. Stoeck [46] presented a new testing methodology for problematic cases of Common Rail injectors, which extends the standard diagnostic procedure by analyzing the resultant fields of the dosed fuel. On the other hand, much

attention was paid to the issues of durability of the piston-rings-cylinder system [47, 48, 49] and the wear of the crankshaft of a marine engine [50], as well as measuring the wear of the engine cylinder [51] and the influence of the start-up temperature on the wear of the cylinder liner [52].

During the start-up of a compression-ignition engine, many negative phenomena and processes are observed that affect not only the engine, but also its surroundings [53]. Hence, the process of starting a compression ignition engine is a phenomenon that attracts the attention of many researchers, which is reflected in the conducted research and published numerous scientific papers [54, 55, 56]. Desantes et al. [57] investigated the influence of nozzle geometry on the ignition and combustion course in the engine chamber of a diesel engine with direct fuel injection during cold start tests. Similar studies, only at low temperatures, were conducted by Pastor Jose et al. [58]. The impact of fuel injector damage during the start-up of a compression-ignition engine in the context of engine vibration activity was investigated by Figlus et al. in [59]. In turn, Jaworski et al. [60] analyzed the accuracy of the obtained test results regarding the emission of an internal combustion engine while driving for cold and hot start-ups. Other studies in various aspects of cold starting of compression-ignition engines were presented in the following research works [61, 62, 63]. Drożdziel in [64] presents the results of operational tests of a vehicle with a diesel engine in terms of the analysis of the start-up electrical parameters. The properties and quality of engine oil also affect the proper course of the start-up process. The tests of engine oils are presented in more detail in [65, 66]. To initiate independent operation of the combustion engine, it is necessary to provide mechanical energy transferred through the crank-piston system from the crankshaft driven by the electric starter [64]. Hence, the technical condition of the starter essentially influences the successful start-up of the internal combustion engine. Diagnostic tests of electric starters of internal combustion engines using various methods are presented in [67, 68, 69].

In this article, tests of a single-cylinder internal combustion engine for non-road applications were considered. In the group of small non-road engines, diesel engines accounted for only 20% of the designs available on the market in 2017. In this group of engines, spark ignition engines are more popular, especially when it comes to low

power [70]. For example, in the case of rescue fans used by the fire brigade in Poland, only one device (and the one with the highest power) is powered by a diesel engine [71]. These engines are subject to different, more liberal regulations [72, 73]. As a result of their lower technical advancement, these engine groups are subject to the following regulations in Europe: for spark ignition engines [74], and for Diesel engines [75].

The article presents selected results of experimental tests on the electrical parameters of the start-up of a single-cylinder compression-ignition engine at constant injector opening pressure and fuel injection advance angle for two fuel doses performed on a dedicated laboratory test setup at the Lublin University of Technology. Experimental tests of the start-up process were carried out under ambient temperature conditions.

TEST SETUP AND METHODOLOGY

The test stand is a four-stroke, single-cylinder engine with direct injection manufactured by Ruggerini Diesel RY125 (Table 1). The most important technical data of this engine are included in Table 1. The starting system consists of a BOSCH starter 0 001 107 090, with a nominal voltage of 12 V and a starter battery with the main parameters: voltage – 12 V, electric capacity – 60 Ah, maximum starting current – 570 A. Main technical data of the starter installed in the research engine are presented in Table 2. The test setup is equipped with equipment for measuring the characteristic parameters of the diesel engine start-up process. On the test setup, information

Table 1. Ruggerini RY125 series engine technical specification [76]

Parameter	Type/value
Engine work cycle	Four-stroke
Injection type	Direct
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

about the position of the engine crankshaft is obtained from the Kübler incremental encoder 8.5820.1312.3600. TP-371, TP-372 sensors with a single processing element (Pt100 platinum resistor) are used to measure cylinder temperature, oil temperature and ambient temperature. The current drawn by the starter is 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 [77]. All measurement signals are recorded using the measurement card National Instruments DAQPad-6070E. A photo of the test setup is presented in Figure 1.

The tests of 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 – hour intervals, with the determined fuel injection parameters and at the ambient temperature. In total, 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 – 21 MPa,
- fuel dose – factory default for idling – FD1 and increased – FD2,
- idle speed – 760 rpm for fuel dose FD1 and 1076 rpm for fuel dose FD2,
- start-up temperature – ambient temperature (in the range of 18.2–22.45 °C).

On the basis of the literature study [53, 78], it can be concluded that there are many definitions of cold and warm starting and engine warm-up in the literature. In the literature on the subject, there are many possibilities of evaluating the start-up

Table 2. Technical data of the BOSCH 0 001 107 090 starter [76]

Parameter	Type/value
Voltage	12 V
Rated power	1.1 kW
Maximum rotational speed	300 rpm
Direction of rotation	Right
Number of pinion teeth	11

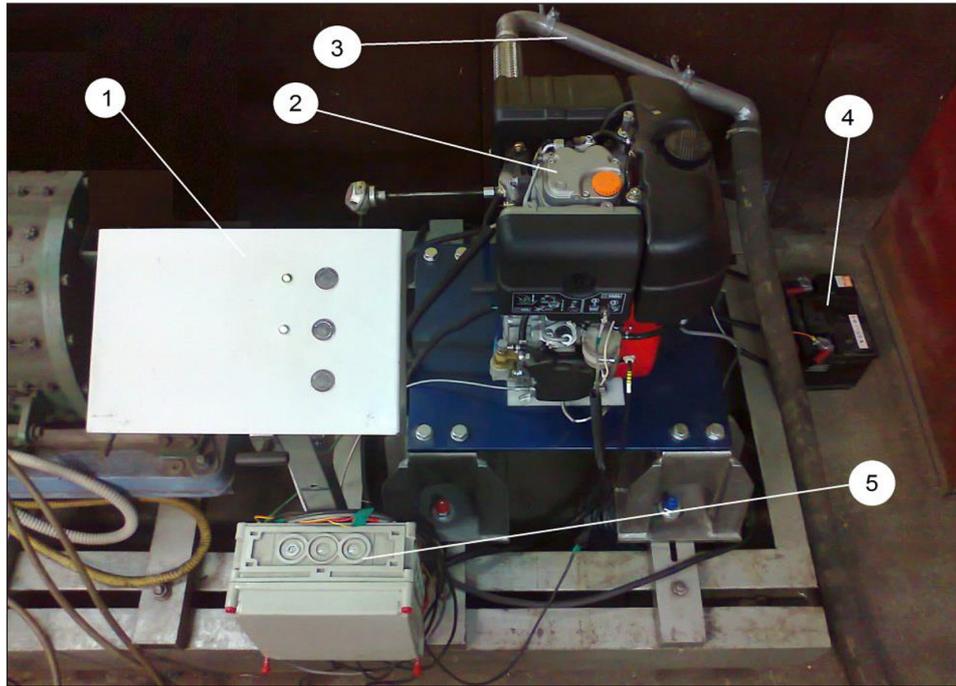


Figure 1. Setup of a single-cylinder diesel engine: 1 – control panel, 2 – single-cylinder engine, 3 – exhaust gas system, 4 – battery, 5 – connection box for measuring output signals [77]

time parameter. In these tests, the start-up time was determined based on the moment of obtaining a stable rotational speed of the engine crankshaft. On the other hand, the starter operation time was determined on the basis of the energy consumption time at the battery terminals. The values and parameters of the start-up process are presented in the form of a graph in Figure 2.

U_{max} is the maximum voltage value that is measured at the battery terminals just before starting the engine [V]. The U_{min} parameter is the minimum voltage value measured at the battery terminals at the beginning of the start-up [V].

U_k is the voltage at the battery terminals after the end of the starting test sample [V]. The I_{max} parameter is the maximum value of the current consumed by the starter at the very beginning of start-up [A]. I_{max} is an indirect measure of the resistance to movement associated with moving the cooperating engine components. As it can be seen from the current waveform (yellow line in the graph), the current changes with the load, visible in the form of an increase in the pressure waveform in the cylinder (further peaks visible with the increase in pressure) and with the crankshaft rotational speed value (red line in the chart).

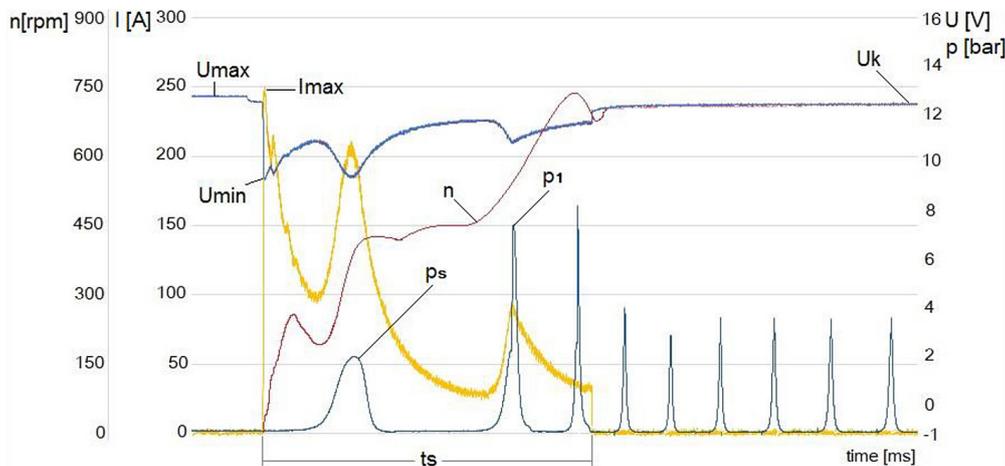


Figure 2. The course of measured parameters during the start-up process

Current consumption decreases to zero as the engine speed increases and the mixture self-ignites, leading to stable ignition and engine operation. Parameter t_s – is the starter operating time [ms], it is the time that elapses from the moment the starter is turned on until the voltage and current reach values corresponding to the starter’s operation without load. The pressure in the combustion chamber is expressed in bars and is presented as a curve in blue and means: p_s – compression pressure and p_f – maximum pressure in the first combustion cycle. The red curve marked by n corresponds to the change in the rotational speed of the engine crankshaft [rpm].

The maximum instantaneous starting power – P_{max} , and average starting power – P_{med} was calculated from the following formulas:

$$P_{max} = U_{min} \cdot I_{max} \tag{1}$$

$$P_{med} = U_s \cdot I_s \tag{2}$$

where: U_s – average voltage of sample of start-up at the battery terminals, V; I_s – average current of sample of start-up, A.

The maximum power during start-up (P_{max}) calculated from formula 1 refers to the maximum current consumed at the beginning of start-up and the minimum voltage occurring at that time. This power is much greater than the power developed by the engine starter (it may be twice as high as the nominal power), but it is a momentary power that is generated for a few milliseconds at the very beginning of the start-up process. Therefore, it can be called the instantaneous maximum

starting power. The PRW-3 injector testing station was used to determine the injector opening pressure and was carried out in accordance with the recommendations of the industry standard BN-84/1301-08 [79]. To determine the value of the fuel injection advance angle, an ETD019.02 FD268 stroboscopic lamp from AVL was used to set the injection advance angle.

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 – I_{max} , the minimum voltage at the beginning of the start-up – U_{min} , maximum power – P_{max} , average starting power – P_{med} and starter operating time – t_s . Start-up tests were carried out at ambient temperature, which is widely used in the literature [16, 53, 80]. The value of the injector opening pressure in both measurement series was 21 MPa. The tests were carried out with 2 fuel doses: nominal fuel dose marked as FD1 and increased fuel dose marked as FD2. The graphs on the horizontal axis show subsequent test trials (30 samples) for engine start-up. Figure 3 presents the distribution of the values of the maximum current consumed by the starter at the beginning of the start-up for two measurement series. As shown in Figure 3, the current value is generally higher in the first measurement series, i.e. at the nominal fuel dose – FD1. For most start-up attempts, the difference between

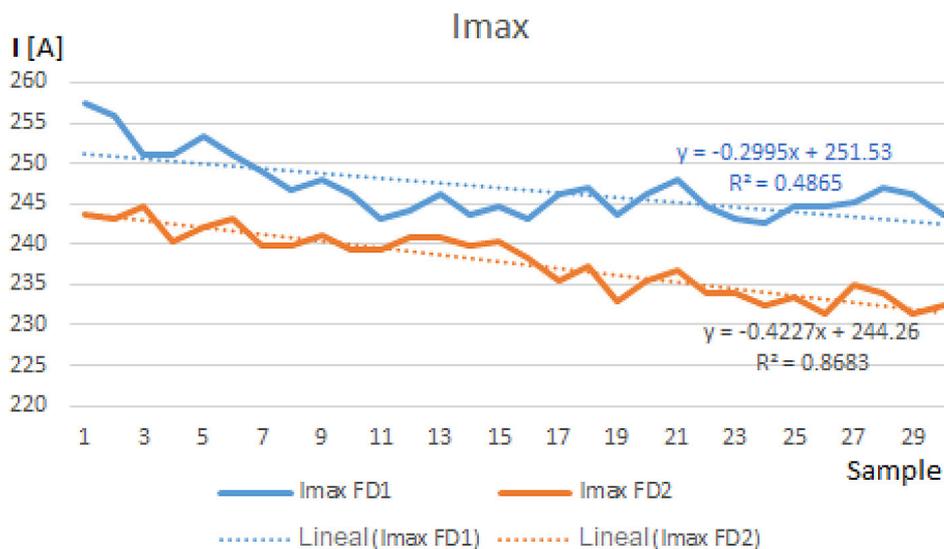


Figure 3. Values of the maximum current consumed by the starter for two measurement series

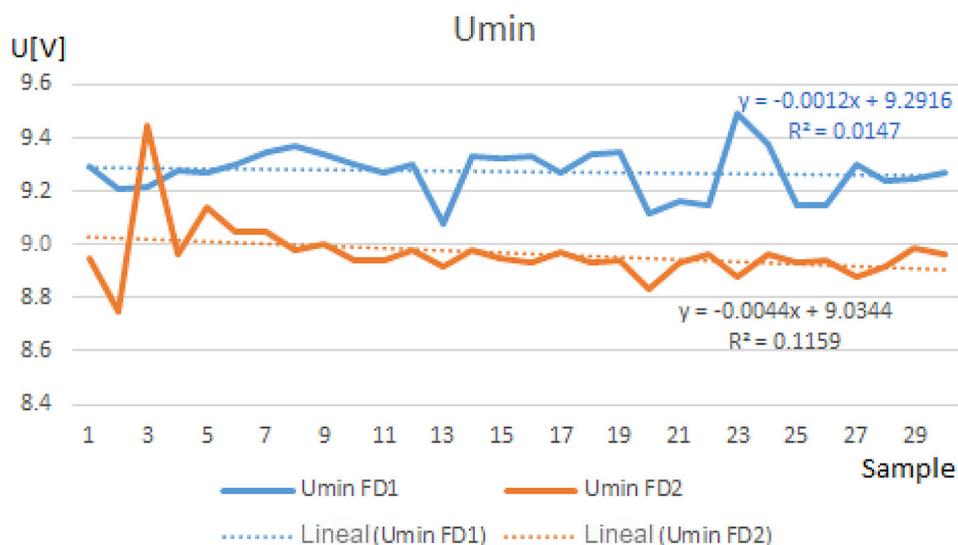


Figure 4. Minimum voltage at the battery terminals at start-up for two measurement series

the series is approx. 15 A, for 6 attempts the difference is smaller and amounts to approx. 5 A. This series was carried out at ambient temperatures of approx. 21 °C. It can be assumed that a larger dose of fuel accelerates the engine start-up and therefore the conditions in the combustion chamber are much better for the engine to start working with lower current consumption by the starter. The starting current is important not only as a measure of the engine resistance to movement, but it can also serve as a diagnostic parameter of the technical condition of the combustion engine. Such an analysis is presented by Ramirez et al., [81] where they analysed electrical parameters for diagnostic purposes of bus engines as a function of compression pressure. Figure 4 shows the distribution of minimum voltage values at the battery terminals at the beginning of the start-up for two measurement series.

When analysing the graph in Figure 4, it can be seen that in the case of the second series, carried out with an increased dose of FD2 fuel, lower values of voltage drop on the starting battery were obtained. This may indicate, similarly to the I_{max} current, that in a series with an increased fuel dose, there are more favourable conditions in the combustion chamber to initiate the engine start-up and its independent operation. Only in one case was the voltage drop greater than in the first series, and this was in the third start-up attempt. Figure 5 presents the distribution of the instantaneous maximum starting power values – P_{max} , calculated based on formula 1. When analysing the course of the graph

in Figure 5, it can be noticed that in the case of the second series, carried out with an increased dose of FD2 fuel, lower values of the instantaneous maximum starting power occurred, which is consistent with the values of the previous parameters presented in the two previous graphs. As indicated earlier, this is a momentary power, much greater than the power developed by the engine starter, and occurs for a short period of time, just a few milliseconds, at the very beginning of the starting process. Figure 6 presents the distribution of average starting power values – P_{med} for two measurement series.

When analysing the course of the graph in Figure 6, it can be seen that in the case of the second series, carried out with an increased dose of FD2 fuel, lower values of the average starting power – P_{med} occurred. It can therefore be concluded that the average starting power is lower with an increased fuel dose, i.e. less energy is needed to initiate the operation of the combustion engine under these ambient conditions. Previous studies presented average values of starting power in the range of 910–922 W [82].

Figure 7 presents another analysed parameter, which is the starter operating time during start-up. Considering the trend line in the case of the starter operation time (Figure 7), there is an opposite tendency than in the case of the other parameters, i.e. the second series with an increased fuel dose – FD2 needed more starter operation time to initiate the operation of the combustion engine. It should be remembered that temperature has a significant impact on the

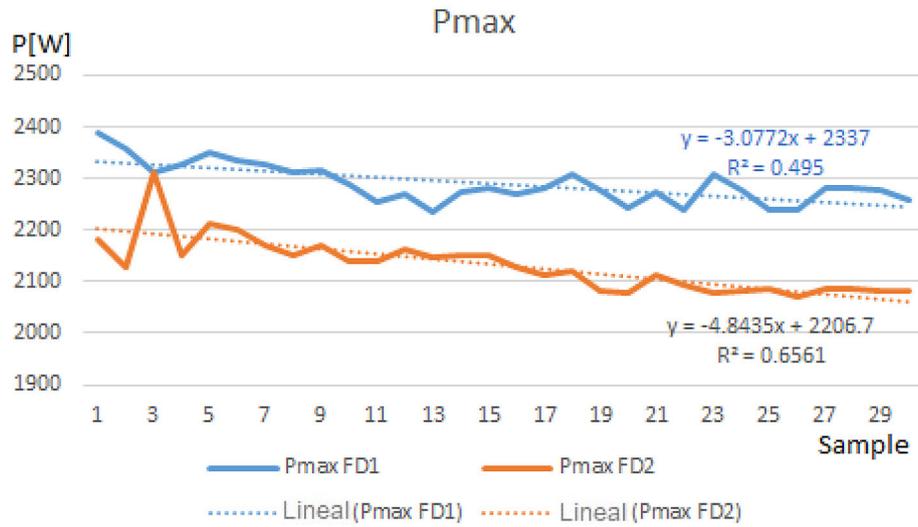


Figure 5. Instantaneous maximum starting power for two measurement series

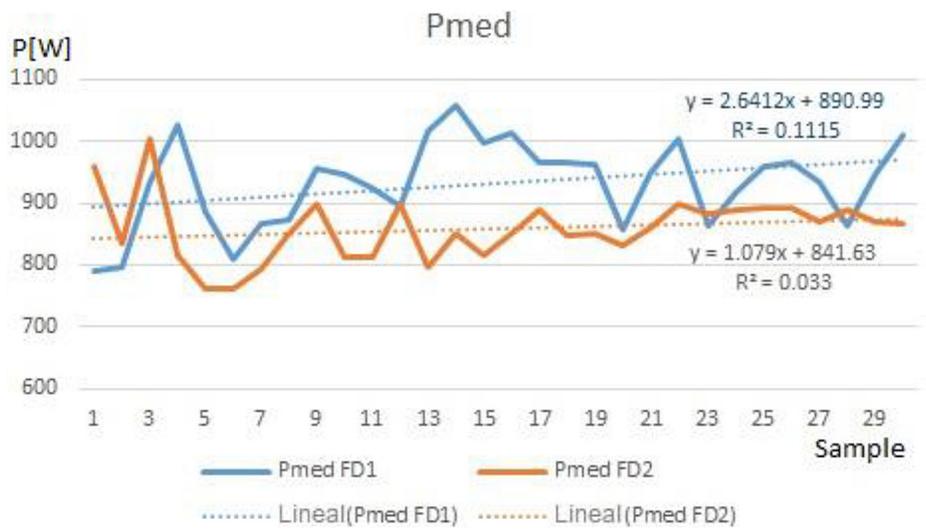


Figure 6. Average starting power – P_{med} for two measurement series

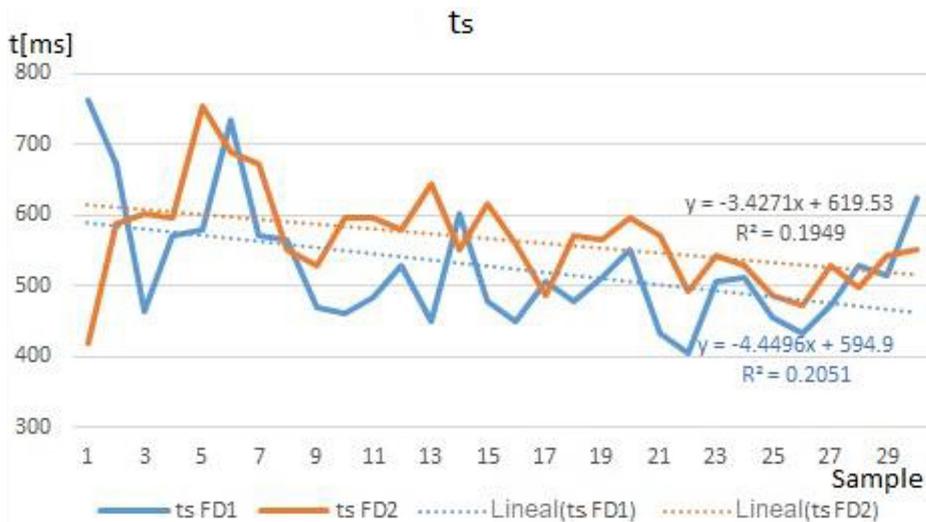


Figure 7. Starter operating time for two measurement series

start-up process of combustion engines, which is confirmed by numerous publications [8, 49, 55] and also on exhaust emissions during cold start-up [78, 80]. In these tests, start-up tests were carried out at positive ambient temperature, but the test temperature in series 2 was slightly lower than in series 1. The difference of 3 °C probably caused a slight extension of the starter operating time, ranging between 20 and 50 ms between starting series, when analysing the differences in the trend line. When analysing specific values of the starter operating time during attempts to start the combustion engine, in series 1 the shortest start-up was 478 ms, while the longest was 763 ms. In the case of a series of 2 starts, the starter operating time values were the shortest 418 ms, while the longest start was 754 ms.

CONCLUSIONS

This paper presents the 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. Start-up tests of the combustion engine were carried out for two doses of fuel FD1 and FD2 at an injector opening pressure of 21 MPa. It turned out that for the first series of measurements with a dose of FD1 fuel, higher values of the measured electrical parameters (I_{max} , U_{min} , P_{max} , P_{med}) were obtained compared to the second series of tests with an increased dose of FD2 fuel. However, in the case of the starter operation time, which is the same as the start-up time of a diesel engine, considering the general tendency, shorter start-up times were obtained for fuel dose – FD1 compared to fuel dose – FD2 of start-up attempts.

The influence of ambient temperature on the start-up process of a compression-ignition engine was also confirmed, which means that for start-up tests carried out in a lower temperature range, slightly above 18 °C, compared to tests at a temperature of approx. 21 °C, a longer starter operation time was observed. The presented tests of 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.

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