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Evaluation of the repeatability of fuel dosing by the common rail fuel supply system

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This study examined the repeatability of fuel dosage in a Common Rail injection system under five operating conditions: idling, full engine load, micro-dosing, full injector load, and high-frequency operation. Using an injection waveform indicator, researchers analyzed the dynamic behaviour of the injection process, including solenoid valve function and signal waveforms, which were compared to injection pressure buildup. Integral and differential injection characteristics were developed for each condition. Results showed the greatest dosing variability during micro-dosing, with a 6.24% variation in injection volume and 7.81% in pressure. In contrast, full engine load showed minimal variation (0.43% and 1.45%). The study concluded that injector component inertia notably impacts dosing consistency, especially at low pressures or short opening times.

Key words: *common rail system, dosage repeatability, single fuel dose, unit dose, IMA code*

1. Introduction

Compression ignition engines continue to be widely used in various types of machinery and vehicles, including construction equipment, agricultural machines, heavy duty trucks, military vehicles, and passenger cars [5]. A key factor contributing to their broad application is the relatively flat torque curve and the generally higher torque output compared to spark ignition engines [11]. The continuous introduction of increasingly stringent exhaust emission standards compels fuel system manufacturers to constantly improve fuel injection systems to meet these regulatory requirements [7]. The implementation of Common Rail systems was a milestone in the development of compression ignition engines. It enabled modern engines to operate more quietly, emit fewer toxic exhaust components, and achieve higher thermal efficiency (with typical compression ignition engines reaching efficiencies around 0.5 compared to 0.4 in spark ignition engines) [1].

The fuel supply system in compression ignition engines is one of the key components affecting exhaust emissions, thermal efficiency, as well as the noise and vibration levels. To meet emission standards and address the demand for reduced fuel consumption and improved engine performance, precise control over the fuel injection process (timing and fuel volume) has become a primary direction in the development of accumulator type fuel systems [13].

Accumulator type fuel systems for compression ignition engines allow for adjustment of multiple injection parameters, including injection pressure, injection timing, duration (and thus the injected dose), and the number of injection phases. The introduction of these systems represented a major technological advancement, which significantly contributed to the reduction of toxic exhaust emissions [23]. The capability of implementing multi-phase injection at pressure levels tailored to engine operating conditions, along with the use of IMA codes allowing the engine control unit to compensate for manufacturing tolerances of individual injectors, has made these systems the standard in modern compression ignition (CI) engines [10].

Despite their relatively high fuel metering precision compared to other fuel systems, discrepancies still exist between the injection parameters intended by the engine control unit and those actually realized. These discrepancies result from various physical phenomena such as pressure wave reflection, fuel compressibility, or changes in fuel properties due to temperature [4]. Fuel temperature increases, among other reasons, as a result of compression in the high-pressure pump. Additionally, due to the arrangement of injectors in the cylinder head and the proximity of high-pressure lines and fuel rail to the heated engine components, the fuel within these elements undergoes heating by absorbing thermal energy from the cylinder head and from compression effects [9].

Given these factors, engineers around the world are conducting studies aimed at understanding the physical phenomena occurring within the fuel system during operation. These investigations are essential for improving compression ignition engines, as a thorough understanding of fuel injection dynamics enables the development of algorithms for improved spray quality control and operating parameter correction. Ultimately, this leads to the design of more fuel efficient engines with reduced emissions of toxic exhaust components and more stable operation.

Ustrzycki et al. presented research on the influence of high-pressure line length on injection process parameters, including fuel dose, injector leakage, and pressure waveform in the injection line upstream of the solenoid injector. The study demonstrated that greater line length leads to greater deviation in injection parameters. This effect is primarily caused by pressure wave oscillations within the high-pressure lines, which depend on fuel pressure, density, and temperature [22].

Tan et al. investigated the influence of injection pressure and injection timing on the combustion characteristics of a high power six cylinder compression ignition engine equipped with a common rail system. The study concluded that increasing the fuel injection pressure reduces exhaust smoke emissions, although it is accompanied by a rise in NO_x emissions. However, combining increased injection pressure with retarded injection timing during low and medium load conditions resulted in simultaneous reductions in both NO_x emissions and smoke levels due to lower combustion temperatures [25].

Slavinskas and Bendziunas [20] focused their research on the impact of biofuels on injection characteristics. The results showed that injection occurs with the lowest velocity when using biodiesel. Furthermore, the greatest injection delay was also observed with biodiesel, which is attributed to its high density – the highest among all the tested fuels.

Xu et al. [24] examined the effects of the shapes and volumes of individual components in the high-pressure circuit of a Common Rail system on the fuel injection process. Their findings indicated that increasing the volume of the fuel rail up to a certain point can effectively reduce the amplitude of fuel pressure fluctuations within the rail. A similar relationship was observed with the diameter of high-pressure lines: increasing the internal diameter of these lines resulted in reduced pressure fluctuations. However, this improvement was only effective up to a certain threshold, beyond which further increases in diameter led to a deterioration in performance.

Rothrock [19] addressed the issue of pressure wave phenomena and pressure fluctuations in common rail systems. His study demonstrated that pressure wave dynamics in the high-pressure circuit can be controlled to improve the quality of fuel injection. Additionally, the research provided insights into how fuel injection systems should be designed to ensure consistent fuel release rates, regardless of engine speed.

Krogerus and Huthala [12] undertook research aimed at identifying the actual injection timing during pilot injection events in Common Rail systems. They developed a method for identifying the relative duration of injection, which was validated through experimental results. This approach allows for the detection and quantification of injection duration drift. Such data can be used for adaptive injection control, enabling the adjustment of injection duration for each cylinder to ensure uniform fuel delivery.

In their study, Chau et al. [4] investigated fuel injection rate, which plays a crucial role in the design and optimization of processes aimed at improving engine efficiency and reducing emissions. Experimental results showed that the injection delay decreases as the injection pressure increases. Additionally, it was observed that the actual injection duration exceeds the duration of the electrical control signal applied to the injector.

Bai et al. [2] conducted experiments to evaluate the effectiveness of a control strategy for mitigating injection dose fluctuations during multiple injection events. The researchers proposed a correction based control strategy in which the input parameters included the relative damping coefficient of the fuel, rail pressure, time interval between injections, and the duration of the injector control signal. Experimental results demonstrated that the proposed correction strategy effectively reduced injection dose fluctuations, with the average fluctuation in individual injection volume decreasing by as much as 44.66%.

The issue of injection dose variability was addressed by Ma et al. [14], who focused on the uneven fuel delivery caused by differences in fuel temperature. Specifically, they investigated the cold start behaviour of a common rail equipped engine at low ambient temperatures. Based on their findings, the volume of fuel injected during a single injection event decreases with a drop in fuel temperature. Additionally, it was observed that the penetration depth of the spray also diminishes as the fuel temperature decreases.

Cavicchi et al. [3] investigated the deviations in injection parameters caused by short intervals between consecutive injections. Their study demonstrated that the properties of biodiesel influence pressure wave oscillations, injection variability, and overall injection rate. Furthermore, the time delay between successive injections significantly affects the parameters of the second injection [15].

Nguen et al. [16] conducted an experimental study to evaluate the accuracy of fuel injection using an injection system mounted on a test bench equipped with a Zeuch type injection analyser. The results showed that for single injection events replicating individual phases of injection, the standard deviation of both injection rate and volume was low. However, in split injection mode, these deviations were significantly larger. Moreover, these parameters were found to depend on injection pressure, the time interval between the parts of the split injection, and pressure wave phenomena occurring in the rail, fuel lines, and the injector itself.

The aforementioned studies illustrate the diversity and complexity of the challenges engineers must address to develop engines that are both fuel efficient and environmentally friendly. A review of the available literature indicates that most injection related studies focus on the influence of various factors – such as fuel type, fuel temperature, geometrical characteristics of common rail system components, and physical phenomena within the system – on the injection process. Some researchers have analyzed injection quality under different injection strategies. Notably, there is a lack of studies addressing the repeatability of consecutive single injection events, which would allow the assessment of an injector's ability to deliver consistent fuel doses.

This study is motivated by the aforementioned research gap and focuses on evaluating the ability of a solenoid injector to perform repeatable injections under five representative engine load states. The limited attention given to this issue may be attributed to the use of Injector Quantity Compensation (IMA – *Injektor Mengen Abgleich*) codes by injector manufacturers. Despite the application of IMA codes, the engine control unit (ECU) cannot precisely predict the injector's behaviour. By applying a control signal of a given voltage and current for a defined duration, the ECU expects the injected fuel quantity to match the injector’s flow characteristics associated with a specific IMA code [6].

The ECU can modify the parameters of the control signal supplied to the injector solenoid based on engine operating data, such as crankshaft speed or even angular acceleration during the power stroke in each cylinder [2]. However, for very small variations in the operating parameters of individual cylinders, the ECU may not apply any correction to the injector control signal. Theoretically, the engine operates according to nominal parameters, but in practice, the individual fuel injection events may differ slightly, potentially affecting the emission of toxic exhaust components – particularly particulate matter. For this reason, the present study investigates the injection dose repeatability of a solenoid injector used in a Common Rail system [16].

Due to the introduction of increasingly stringent exhaust emission standards for internal combustion engines, research on fuel injection systems has largely focused on spray quality and the combustion process of the air-fuel mixture within the engine's combustion chamber. When studies regarding the fuel injection process are published, they are primarily concerned with the main injection dose. At present, as the main fuel injection process has been extensively optimized and the injection of large doses is precisely controlled by the engine control unit, small fuel doses remain problematic in terms of injection precision, accuracy, and repeatability. These small doses play a significant role in determining the emission levels of toxic exhaust components.

It should also be noted that during one full engine cycle, the injector performs a single main injection event, characterized by high injection pressure and a relatively long injector opening time. In contrast, small volume injections, often referred to as micro injections (e.g., pilot or post injections), are executed multiple times within a single engine cycle. Therefore, it is essential to investigate the stability and repeatability of small-volume injections.

The objective of the present study was to assess the injection dose repeatability of a solenoid injector used in common rail fuel systems by employing indirect measurement methods. These methods involved injecting fuel into a long measurement line.

The test conditions proposed in this study are representative of the operating conditions of a compression ignition engine. In such engines, fuel injection occurs at the end of the compression stroke – when the pressure in the combustion chamber is at its highest. This pressure acts upon the nozzle surface, the nozzle holes, and the fuel spray itself. During the experimental investigation, similar pressure conditions were replicated, exerting force on the nozzle tip and the injected fuel stream. In the test setup, the combustion chamber was simulated by a dedicated measurement section consisting of a pipe with a defined cross section, in which pressure was regulated using a control valve. This allowed the injection process to take place under conditions closely resembling those found in real engine operation.

2. Object and research methodology

The tests were carried out based on a brand new BOSCH electromagnetic injector, marked with code 0445110038, from a Renault Espace III car equipped with a 2.2 DCI engine. This engine is characterized by the following parameters: power – 96 kW, torque – 290 Nm, compression ratio – 18.3. The common rail system of this engine is powered by a high-pressure pump marked CP1H3 with the following parameters: maximum working pressure – 135 MPa, number of pistons – 3, maximum capacity – 85 mm^3 per cycle, absorbed power – approx. 3.5 kW, pressure control – regulation on the suction side using a high-pressure regulator.

It is impossible to directly measure the volume of fuel supplied by the injector during a single injection, because the volume of fuel injected during a single injection is too small to be measured directly [17]. For this reason, an injection progress indicator was used to carry out the test, which allows injection into a chamber of constant volume.

In this method, a liquid replacing diesel fuel is injected into a chamber filled with the same substance under low pressure [20]. The chamber with a constant volume will be referred to as the combustion chamber in the rest of the article. The substance used for the tests was the Kalibrol test fluid due to safety conditions (requirement of non-flammability of the fluid used for testing). This is a fluid with a precisely defined viscosity (3 cSt at 40°C) by the ISO 4113 standard. It is characterized by low compressibility and good rheological properties. Meeting the ISO 4406 cleanliness standard, it is a fluid free from impurities that may damage the moving elements of the injector. In addition, it is chemically neutral to materials commonly used in fuel systems. It is also adapted to work in a wide temperature range to simulate various operating conditions of the injector. In the rest of the article, this liquid will be referred to as fuel. This is a substance dedicated to the measuring system used in the Pump and Injector Testing Station (STPiW-2, *Stanowisko Testowania Pomp i Wtryskiwaczy)* test bench. This testing station allows for configurable control of the Common Rail injector operation – adjustment of opening time, frequency, and fuel pressure.

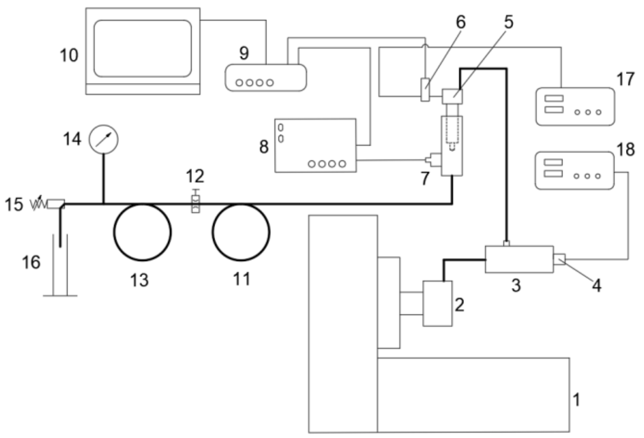

Fig. 1. Schematic diagram of the test stand (thick line – hydraulic lines, thin line – electrical lines): 1 – STPiW-2 test bench, 2 – high-pressure pump, 3 – common rail, 4 – pressure control valve, 5 – injector, 6 – current clamp, 7 – pressure sensor, 8 – current amplifier, 9 – oscilloscope, 10 – portable computer, 11 – measuring tube, 12 – throttle valve, 13 – discharge tube, 14 – pressure gauge, 15 – relief valve, 16 – measuring vessel, 17 – injector controller, 18 – high-pressure pump controller

The schematic of the stand is presented in Fig. 1. The AVL QL61D pressure sensor ensured precise pressure measurements, while the FLUKE 80i-110s current clamps measured the injector control current. During the experimental tests, a Handyscope HS5 digital recorder with a resolution of 16 bits and a sampling rate of up to 500 MHz was employed to record the waveforms of the individual signals. The use of such a high resolution enabled more accurate sampling of the original signal, significantly reducing the quantization error compared to standard A/D converter systems with 12-bit resolution. For direct measurements, multi-channel software, dedicated to the Handyscope HS5, was used. This software facilitated the recording, archiving, and preprocessing of waveforms - for example, extracting individual injector cycles. Final processing and graphical presentation of the results were performed in MS Excel.

The measurement ranges and accuracies of the equipment used for the tests are listed in Table 1.

Table 1. Summary of measurement ranges and accuracy of measuring devices

Device	Task	Measurement range	Accuracy
FLUKE 80i-110s Current Clamps	Injector control current measurement	0.1–100 A DC/ 0.1–70 A AC	±4%
AVL QL61D pressure sensor	Measurement of instantaneous pressure values in the injection indicator	0–200 MPa	0.249 pC/MPa
KFM digital manometer	Measuring the liquid pressure in the discharge pipe	0–10 MPa	0.01 MPa

The study and development of results involved measuring the voltage and electric current characteristics of the pressure sensor and recording the voltage signal using a portable computer. Subsequently, the voltage value of each sample was converted to the appropriate value (pressure or electric current), and the fuel injection runs were derived from the recorded data. From the recorded signals, the characteristics of the fuel injection process were determined in two forms:

- differential form: illustrating how the fuel flow rate through the injector nozzle changed during the entire injection time
- integral form: showing how the total volume of fuel in the indicator chamber changed over time.

The assessment of fuel dosing repeatability was based on:

- graphic interpretation of the obtained characteristics
- calculated injection doses
- comparative analysis of the peak pressure and current values in each waveform
- statistical parameter lists of the current intensity and injected fuel pressure at selected characteristic operating points of the injector.

During the repeatability testing of fuel dosing, the injector opening time was varied depending on the simulated engine load. Parameters such as the rail pressure and fuel injection frequency were also adjusted. During the test, the rotational speed of the high-pressure pump shaft remained constant – the pressure in the fuel rail was regulated by changing the duty cycle of the current signal in the pressure regulator (PWM regulation). The system pressure was set to 3.8 MPa using the indicator discharge valve [18]. During the tests, the injector operated under conditions corresponding to its characteristic points.

The tests were conducted for the following engine load conditions, corresponding to the operating parameters of the injector:

- idle: standard injector operating conditions at low engine speed
- full engine load: the longest injector opening time
- full injector load: the highest fuel pressure
- injector distribution capacity: the highest injector operating frequency
- minimum fuel doses (hereinafter referred to as "microdoses"), the shortest injector opening time.

Testing the injector operation in these characteristic operating conditions allows for precise analysis and evaluation of the phenomena occurring inside it during various load states of the injector [21].

The injector operating parameters are presented in Table 2.

Table 2. Injector operating parameters for individual engine load conditions

No.	Load status	Injector opening time	Fuel pressure in the fuel tank	Injection frequency
1.	Engine idle	600 μs	40 MPa	10 Hz
2.	Full engine load	1000 μs	100 MPa	20 Hz
3.	Full load on injectors	600 μs	140 MPa	10 Hz
4.	Injector division capacity	500 μs	100 MPa	40 Hz
5.	Microdoses of fuel	300 μs	30 MPa	20 Hz

When the engine is idling, the crankshaft rotates at a low speed. At this operating condition, the engine generates low torque, which is sufficient to overcome the engine's resistance and ensure stable operation. To achieve such engine operating conditions, the injectors introduce a small dose of fuel into the combustion chamber. As a result, the injectors remain open for a short duration (approximately 600 μs), and the pressure in the accumulator is maintained at a low level (approximately 40 MPa). The injector opening frequency is also low – 10 Hz.

During full engine load, the engine must generate maximum torque. An increase in the injected fuel dose leads to an increase in the torque exerted on the crankshaft. To achieve this, the injectors must remain open for a sufficiently long duration (1000 μs), and the fuel pressure in the accumulator is relatively high (100 MPa). Greater torque is generated at higher engine speeds; hence, the injection frequency is already higher (20 Hz).

One of the measurement series in the tests focused on the injector's performance during full load operation. In this state, the injector opening time was shorter than during full engine load (600 μs), although the liquid pressure in the fuel tank was the highest (140 MPa). The injection frequency was 10 Hz. The main objective of this measurement series was to analyse the injector's behaviour when its components were subjected to high liquid pressure.

To evaluate the injector's ability to perform injections in rapid succession, another series of measurements was conducted with a short injector opening time (500 μs). The liquid pressure in the fuel tank was set to 100 MPa, and the injection frequency was 40 Hz.

The common rail system enables the implementation of multi-phase injection, where, in addition to the main injection dose, smaller doses are also injected. To test the injector's ability to implement small injection doses, a dedicated measurement series was carried out, measuring the injection dose volume for a very short injector opening time

(300 μs) and low liquid pressure in the fuel tank (30 MPa). Because small pre-injection doses follow one another in short time intervals, the injection frequency in this measurement series was set to 20 Hz.

3. Calculation method and adopted simplifications

Placing the injector outlet in a pipe filled with fuel allows pressure changes to be observed at any cross-section of the pipe. These changes are proportional to the fuel flow rate from the nozzle outlet of the injector being tested. By throttling the fuel flow from the measuring pipe, it is possible to maintain a pressure level within the pipe that corresponds to the pressure in the cylinder at the end of the compression stroke.

Figure 2 presents the current control curve of the solenoid valve coil and the pressure increase curve in the indicator measuring section. The visible shift in pressure results from the delay introduced by the time required for the injector to open after the control current is applied, as well as the time required to close the injector after the control voltage is cut off.

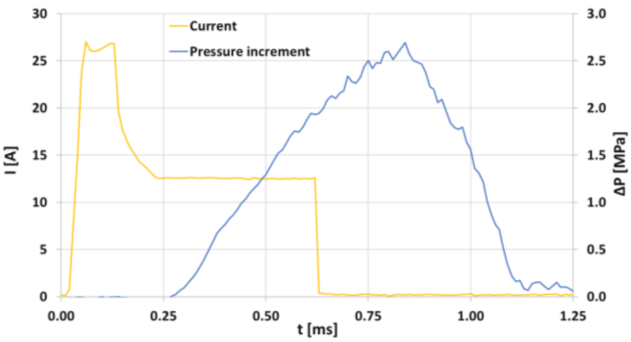

Fig. 2. Shift of the pressure waveform relative to the control current wave form

By using appropriately scaled data, it was possible to create a plot of the electric current intensity profile controlling the solenoid valve coil of the injector, as shown in Fig. 3a. In addition, a plot of the pressure increase in the measuring section of the injection course indicator was also created, as shown in Fig. 3b.

The fuel injection characteristic illustrates the relationship between the amount of fuel injected into the cylinder during a single injection and the engine crankshaft rotation angle or time. The amount of fuel is usually expressed in units of volume. The injection characteristic is presented in two forms: differential and integral.

The differential form depicts the instantaneous fuel flow rate from the injector nozzle during a single injection cycle as a function of time. This relationship is described by eq. 1.

$$\frac{dq}{dt} = f(t) \qquad (1)$$

where: q – fuel dose value in cm^3 per injection, t – time in ms.

The surface area bounded by the ordinate, the abscissa, and any section of the characteristic curve described in this form is directly proportional to the amount of fuel delivered to the cylinder during the considered time period.

a)

b)

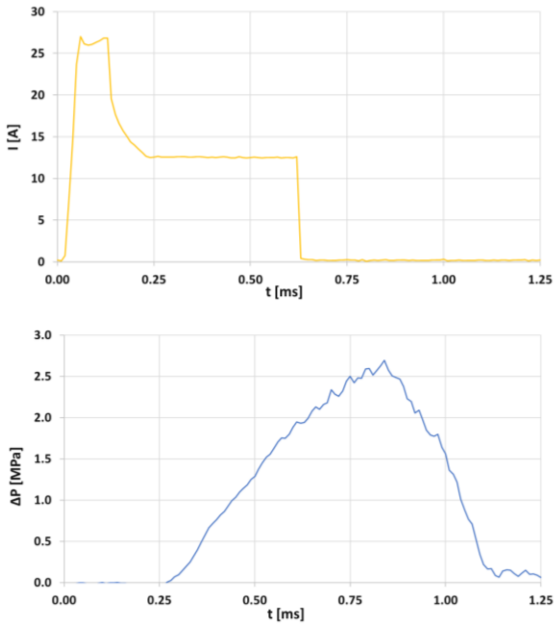

Fig. 3. Example results of direct measurements: a) course of the current controlling the solenoid valve coil of the injector, b) course of changes in the fuel pressure in the injection indicator

The integral form depicts the total variation of fuel supplied to the cylinder from the start of injection to the moment under consideration, expressed as a function of time.

The integral characteristic is represented by eq. 2:

$$\int_{t_0}^{t_x} \frac{dq}{dt}\, dt = F(t) \text{ , that is } q = F(t) \qquad (2)$$

where: t_0 – time corresponding to the start of injection, t_x – the time corresponding to the moment under consideration.

The injection characteristic is more commonly defined in the differential form, as it illustrates the intensity of fuel saturation in the air contained within the engine combustion chamber. This characteristic affects the process of fuel evaporation, its mixing with air, and consequently the course of combustion. The shape of the characteristic significantly impacts the length of the preparatory period for combustion, the rate of combustion pressure increase, the peak pressure during combustion, and the indicated efficiency of the cycle.

According to one of the fundamental fluid dynamics relationships, an increase in the velocity of a fluid within a pipe is proportional to the amplitude of the pressure wave caused by this velocity change, as expressed by eq. 3:

$$a \cdot \rho \cdot dw = dp \qquad (3)$$

where: a – speed of sound in the considered liquid in m/s, ρ – density of the liquid under consideration in kg/m^3, w – liquid flow velocity in m/s, p – liquid pressure in Pa.

When a liquid flows through a pipe with a cross-sectional area F [m^2], the stream continuity equation, assuming small pressure changes and negligible effects from liquid elasticity and pipe wall deformation, takes the form of equation 4:

$$\frac{dq}{dt} = F \cdot w \tag{4}$$

where: q – the dose of liquid flowing through a given cross-section, F – cross-sectional area through which the fluid flows.

Since the density of hydrocarbon fuels and the speed of sound in the pressure range typical of fuel injection are only slightly dependent on pressure, the equation can be simplified as shown in equation 5:

$$a \cdot \rho \cdot w = p \tag{5}$$

Knowing the speed of sound in the liquid, its density, and pressure, the flow velocity of the liquid stream can be calculated using equation 6:

$$w = \frac{p}{a \cdot \rho} \tag{6}$$

Using equation 4 and knowing the flow velocity of the liquid stream, the fuel flow rate can be calculated. This value determines the fuel flow rate in [m³/s]. In engineering practice, the flow rate is typically expressed in [mm³/s]. The relationship is shown in equation 7:

$$\frac{dq}{dt} = 10^9 \cdot F \cdot w \tag{7}$$

To obtain a differential fuel injection characteristic, the flow rate was differentiated with respect to time, where the time interval equalled the pressure sensor sampling period (0.01 ms). The resulting run is shown in Fig. 4a.

By integrating the flow rate from the start of fuel injection to the injector closing time, the fuel injection characteristics in integral form were derived, as shown in Fig. 4b.

a)

b)

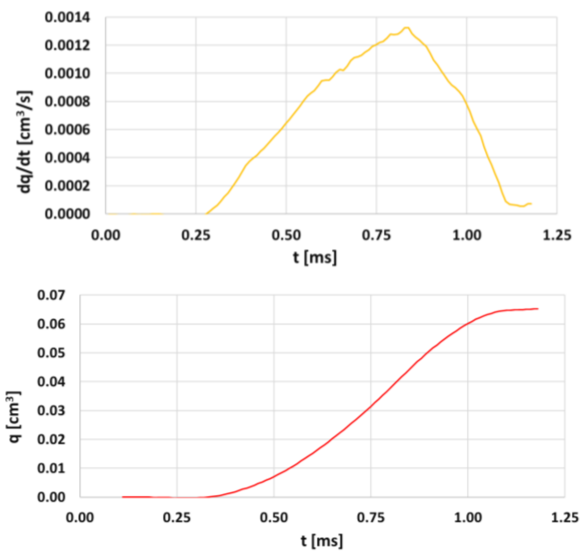

Fig. 4. Fuel injection characteristics determined based on tests in a) differential, b) integral form

In the discussed method, measuring the fuel flow rate is simplified to measuring the instantaneous pressure at a given cross-section of the pipe filled with fuel. For the calculations, the following assumptions were made:

a = 1400 m/s (speed of sound in the liquid under consideration)

p = 832.9 kg/m³ (density of the liquid under consideration)

F = 0.00001512 m² (cross-sectional area through which the liquid flows in the measuring section).

4. Analysis of research results

4.1. Introduction

After completing the site tests, the following were analyzed:

- the maximum liquid pressure during the injection process to assess the correlation between the injection dose variation coefficient and the injection pressure variation coefficient
- the determined volume of each injected dose to evaluate the repeatability of dosing, which impacts the emission of toxic exhaust components and the uniformity of engine operation
- the shape of the injection characteristic in both differential and integral forms to assess the nature of the liquid injection process
- the relationship between the injector solenoid valve actuation time and its opening time to evaluate the effect of the inertia of injector components on the speed of its opening and closing.

The coefficient of variation (CV), used in this study to evaluate the test results, is a standardized measure of the variation in the distributions of a given characteristic. It is defined as the ratio (σ) of the standard deviation to the mean (μ):

$$CV = \frac{\sigma}{\mu} \tag{8}$$

4.2. Engine idle

In this state of engine operation, the injector introduces small volumes of fuel into the combustion chamber to maintain a low and constant engine speed under no load. The solenoid valve coil actuation time of the injector was brief (600 μs in this case), and the injection pressure remained relatively low (40 MPa). At idle speed, due to the low engine speed, the injector operated at an injection frequency of 10 Hz.

In the electric current intensity profile controlling the injector, as shown in Fig. 5a, a short period can be observed during which the solenoid valve coil is supplied with an attraction current exceeding 25 A, which is maintained for approximately 0.15 ms. For the remainder of the period, the holding current is roughly half the magnitude of the attraction current.

In the initial stage of the attraction current waveform, a disturbance is visible, where, after reaching the peak current intensity, the value drops rapidly before stabilizing. This phenomenon results from the impact of the solenoid valve anchor on the front surface of the coil. The change in current intensity in the valve coil circuit does not occur abruptly; a gradual increase in the electric current intensity is noticeable. This behaviour is a direct consequence of the properties of the induction coil, where the current intensity cannot change instantaneously, as dictated by the first law of commutation [8].

The volume of fuel dosed during injection did not change rapidly; instead, the fuel supply was smooth, as confirmed by the smooth course of the differential fuel injection characteristic shown in Fig. 5b. This characteristic takes the shape of a run, which results from the injector's opening and closing process.

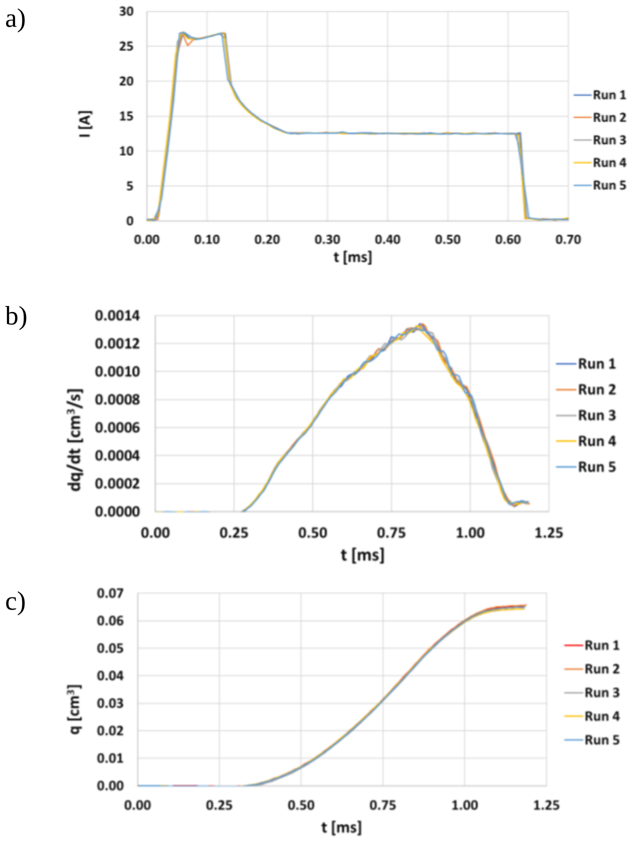

Fig. 5 Injection runs and characteristics obtained from a series of measurements under idle running conditions: a) run and intensity of the current supplying the injector solenoid valve coil, b) fuel injection runs and characteristics in differential form, c) fuel injection runs and characteristics in integral form

The gentle pressure build-up is attributed to the relatively long time it takes for the injector needle to rise, a delay caused by the inertia of the valve anchor and the injector needle. Additionally, the control chamber contributes to the extension of the injector opening time, as fuel must flow out through the outlet choke after the valve anchor has risen. Similarly, the gentle pressure drop can be explained by the need to fill the control chamber through the intake choke, where the fuel pressure exerts a force on the needle plunger, thereby closing the injector.

The integral characteristic is shown in Fig. 5c. In its central part, a linear increase in the fuel dose is evident, indicating that the fuel flow rate through a given cross section is directly proportional to the pressure generated in that cross section.

Characteristic values and statistical parameters of the injections are presented in Table 3.

4.3. Full engine load conditions

This test was carried out using injection parameters corresponding to full engine load conditions. The injector opening time was the longest, at 1000 µs, to achieve a large injection dose. The injection pressure was high (100 MPa). This is necessary because the engine must generate sufficient torque on the crankshaft to exceed the torque loading on the engine.

Table 3. Summary of injection process parameters for engine idle speed

Injection	The volume of fuel injected during individual injections [mm^3]	Maximum pressure for each injection [MPa]
Run 1	0.01672	2.694
Run 2	0.01682	2.682
Run 3	0.01656	2.678
Run 4	0.01650	2.667
Run 5	0.01666	2.615
The highest value	0.01682	2.694
Minimum value	0.01650	2.615
Statistical parameters		
Average value	0.01665	2.667
Standard deviation	0.00011	0.027
The difference between the highest and lowest value	0.00032	0.078
Coefficient of variation [%]	0.69	1.024
Injector control time [ms]	0.620	
Pressure rise time [ms]	0.860	
Control time/pressure duration*100%	72	

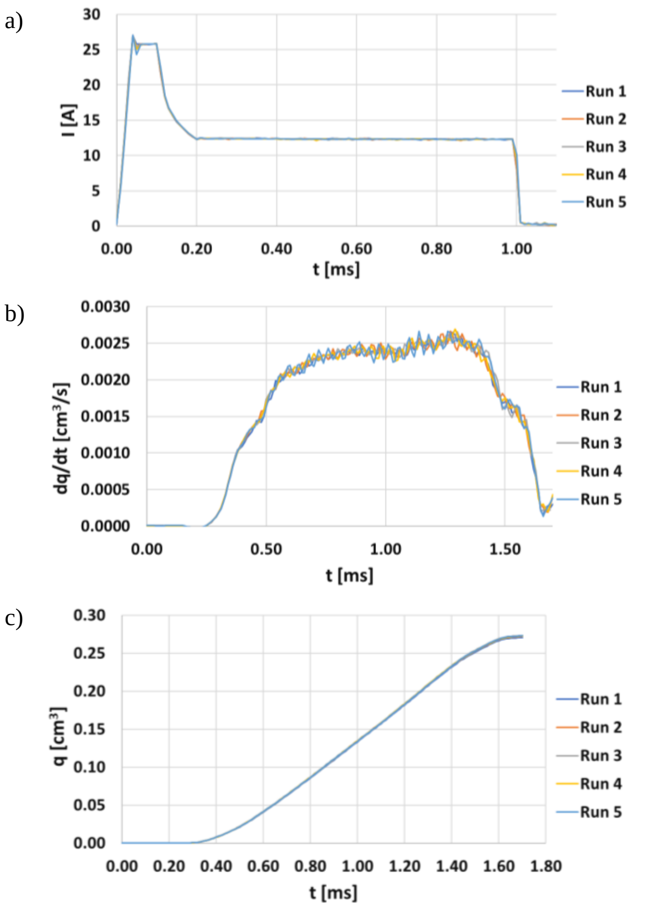

Fig. 6. Injection runs and characteristics obtained from a series of measurements under full engine load conditions: a) run and intensity of the current supplying the injector solenoid valve coil, b) fuel injection runs and characteristics in differential form, c) fuel injection runs and characteristics in integral form

For the injector operating under full engine load conditions, attention is drawn to the significantly longer holding current, with no change in the duration of the period during which the attraction current flows through the coil winding, as shown in Fig. 6a.

Based on the observed fluctuations in flow rate after the injector was fully open, it can be concluded that the fuel pressure at the nozzle outlet was not constant during this period. This inconsistency may be attributed to the turbulent nature of fuel flow through the injector channels.

The integral characteristics of individual injections, as shown in Fig. 6c, "overlap." Based on the graphical evaluation of these characteristics, it can be concluded that the repeatability of fuel dosing at a relatively long opening time and high fuel pressure is high. This conclusion is further supported by numerical values, particularly the coefficient of variation, included in Table 4, which presents characteristic values and statistical parameters for the discussed engine load condition.

The characteristic values and statistical parameters of the injections for this engine load condition are presented in Table 4.

Table 4. Summary of injection process parameters for full engine load

Injection	The volume of fuel injected during individual injections [mm³]	Maximum pressure for each injection [MPa]
Run 1	0.0693	5.341
Run 2	0.0698	5.343
Run 3	0.0699	5.287
Run 4	0.0698	5.393
Run 5	0.0703	5.517
The highest value	0.0703	5.517
Minimum value	0.0693	5.287
Statistical parameters		
Average value	0.0698	5.76
Standard deviation	0.0003	0.078
The difference between the highest and lowest value	0.0009	0.230
Coefficient of variation [%]	0.43	1.451
Injector control time [ms]	1.010	
Pressure rise time [ms]	1.400	
Control time/pressure duration*100%	72	

4.4. Full load on injectors

During the tests of the injector under full load conditions, the fuel pressure was the highest among all the measurement series (140 MPa), as the greatest forces were exerted on the components inside the injector.

When the injector operates under full load conditions, a nonlinear increase in the fuel flow rate within the measuring section of the indicator is observed, similar to the behaviour observed under full engine load conditions.

For fuel injection characteristics in integral form, the courses of individual injections are also similar in shape and nearly overlap. This indicates a high level of dosing repeatability for these fuel injection parameters, consistent with the results observed under full engine load conditions. In both cases, the injector opening time and fuel pressure were high compared to those observed under other engine load conditions.

The characteristic values and statistical parameters of the injections for this engine load condition are presented in Table 5.

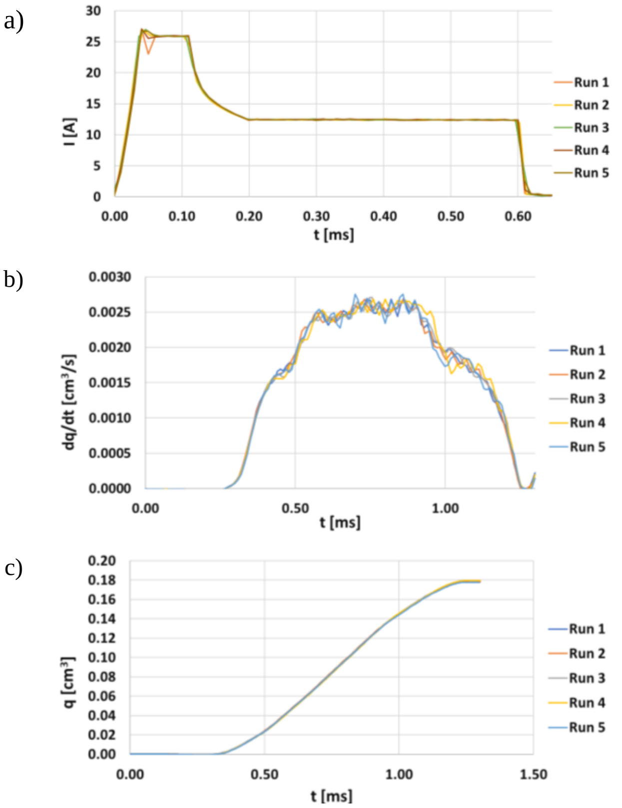

Fig. 7. Injection runs and characteristics obtained from a series of measurements under full load conditions of the injector: a) run and intensity of the current supplying the injector solenoid valve coil, b) fuel injection characteristics in differential form, c) fuel injection characteristics in integral form

Table 5. Summary of injection process parameters for full injector load

Injection	The volume of fuel injected during individual injections [mm³]	Maximum pressure for each injection [MPa]
Run 1	0.0457	5.478
Run 2	0.0459	5.344
Run 3	0.0461	5.446
Run 4	0.0462	5.388
Run 5	0.0457	5.683
The highest value	0.0462	5.683
Minimum value	0.0457	5.344
Statistical parameters		
Average value	0.0456	5.468
Standard deviation	0.0002	0.117
The difference between the highest and lowest value	0.0005	0.339
Coefficient of variation [%]	0.42	2.143
Injector control time [ms]	0.61	
Pressure rise time [ms]	0.98	
Control time/pressure duration*100%	62	

4.5. Injector division capacity

During this measurement series, the distinguishing parameter, compared to other series, was the high injection frequency of 40 Hz. This part of the study aimed to evaluate how the injection proceeds when the injector operates at such a high frequency. The ability to perform repeatable injections under these conditions is important, as the initial injection phases during engine operation occur within short time intervals, resulting in a high frequency of pre-injections.

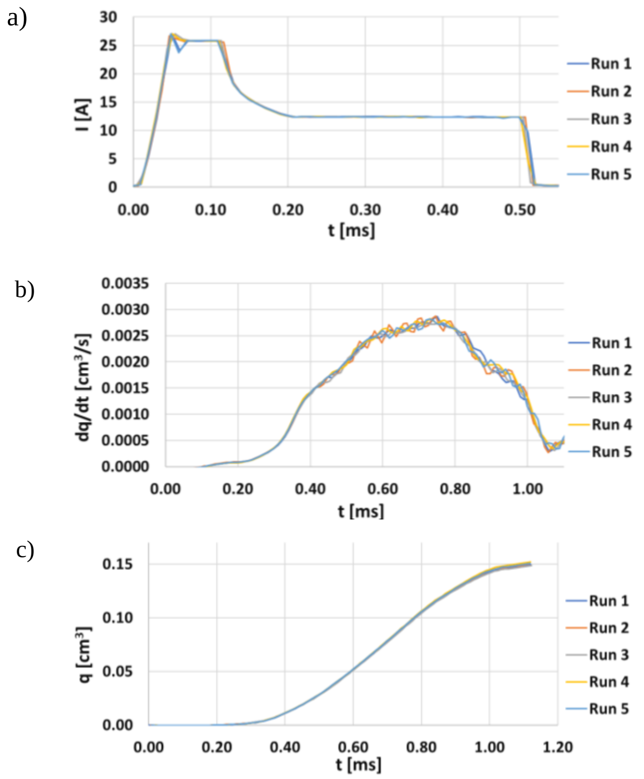

Fig. 8. Injection runs and characteristics obtained from a series of measurements under the conditions of testing the division ability of the injectors: a) run and intensity of the current supplying the solenoid valve coil of the injector, b) fuel injection characteristics in differential form, c) fuel injection characteristics in integral form

In the discussed case, the fuel injection characteristic in the differential form exhibits a disturbance characterized by a nonlinear increase in the volume of injected fuel. After exceeding a flow rate of 0.0015 mm^3/s, the rate of increase in fuel flow through the nozzle becomes smaller. The next inflection point in the runs occurs at a flow rate of approximately 0.0025 mm^3/s. These inflection points are mirrored on the falling edge for the same flow rate values.

The integral fuel injection characteristic runs reach their peak values almost simultaneously. This indicates that the total volume of fuel injected during each injection was practically the same, suggesting that the higher injection frequency does not significantly affect the repeatability of fuel dosing. This conclusion is further supported by statistical parameters, as the coefficient of variation for the volume of fuel injected during individual injections is 0.72. For the measurement series corresponding to full engine load and full injector load conditions, this coefficient was 0.43 and 0.42, respectively.

The characteristic values and statistical parameters of the injections are presented in Table 6.

Table 6. Summary of injection process parameters for the injector's division capacity

Injection	The volume of fuel injected during individual injections [mm^3]	Maximum pressure for each injection [MPa]
Run 1	0.0384	5.754
Run 2	0.0386	5.841
Run 3	0.0382	5.488
Run 4	0.0391	5.633
Run 5	0.0388	5.637
The highest value	0.0391	5.841
Minimum value	0.0382	5.488
Statistical parameters		
Average value	0.0386	5.671
Standard deviation	0.0003	0.120
The difference between the highest and lowest value	0.0008	0.353
Coefficient of variation [%]	0.72	2.116
Injector control time [ms]	0.51	
Pressure rise time [ms]	0.85	
Control time/pressure duration*100%	60	

4.6. Microdoses

During the measurement series corresponding to microdoses, parameters such as fuel pressure and injector opening time were the lowest among all measurement series conducted so far. Microdoses represent the initial injection phases, such as pre-injection, during which a small volume

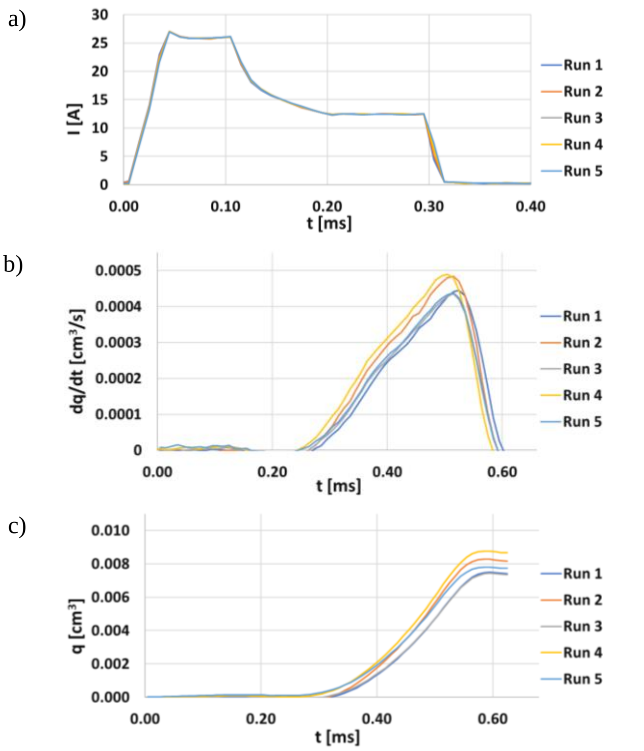

Fig. 9. Injection runs and characteristics obtained from a measurement series under conditions of micro doses: a) run and intensity of the current supplying the solenoid valve coil of the injector, b) fuel injection characteristics in differential form, c) fuel injection characteristics in integral form

of fuel is introduced into the combustion chamber to initiate the combustion process. In this series, the fuel pressure in the rail was 30 MPa, and the injector opening time was 300 μs.

The shapes of the fuel injection characteristics in the differential form clearly indicate that the fuel was injected into the measuring section of the indicator in a largely consistent manner, albeit not entirely uniform. The rising edges of the runs show minimal deviation from straight lines, which may suggest laminar fuel flow through the injector.

The injection courses during the implementation of microdoses differ significantly from those observed in other tests. The fuel doses injected during each course vary considerably, as evidenced by the differing peak values of the injected fuel volumes – the runs do not converge at a single peak value. Additionally, the coefficient of variation for the fuel volume injected during individual injections is the highest recorded so far, at 6.25. This value is more than 11 times greater than the average coefficient of variation observed in all previous measurement series, which was 0.565.

The characteristic values and statistical parameters of the injections for this measurement series are presented in Table 7.

Table 7. Summary of injection process parameters for microdoses

Injection	The volume of fuel injected during individual injections [mm^3]	Maximum pressure for each injection [MPa]
Run 1	0.0019	0.884
Run 2	0.0021	0.962
Run 3	0.0019	0.783
Run 4	0.0022	0.893
Run 5	0.0020	0.791
The highest value	0.0022	0.962
Minimum value	0.0019	0.783
Statistical parameters		
Average value	0.0020	0.863
Standard deviation	0.0001	0.067
The difference between the highest and lowest value	0.0003	0.179
Coefficient of variation [%]	6.25	7.806
Injector control time [ms]	0.31	
Pressure rise time [ms]	0.35	
Control time/pressure duration*100%	89	

5. Discussion and results

Figure 10 compares the injection dose variation coefficients and pressure variation coefficients across the characteristic injector operating conditions. Greater discrepancies were observed for the injected fuel pressure, which, for all operating conditions, showed higher values than the injection dose variation coefficient. These discrepancies may have been influenced by pressure wave phenomena occurring in the measuring section of the injection course indicator. It is important to note that similar phenomena occur in the fuel tank, high-pressure pipe, and inside the injector itself.

For microdoses, both coefficients differ significantly in value from those observed under other conditions. Based on this comparison, it can be concluded that as pressure and injector opening time increase, the repeatability of fuel dosing improves.

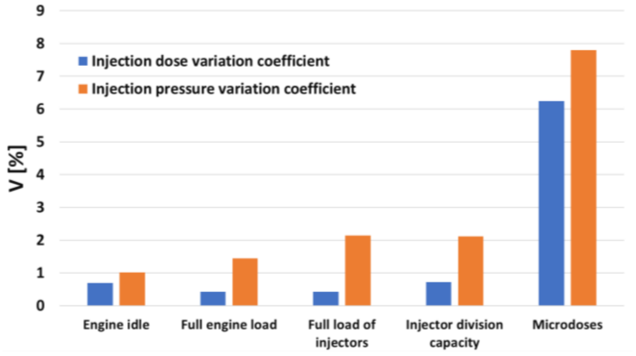

Fig. 10. Summary of the injection dose variation coefficients and injection pressure values depending on the engine load

Table 8 presents the following parameters:
- average value
- standard deviation
- the difference between the smallest and largest value
- coefficient of variation, for the volume of injected liquid and the pressure value.

Additionally, the table compares the ratio of the solenoid valve coil control time to the duration of the pressure in the indicator chamber.

Table 8. Summary of injection process parameters for individual injector operating states

Parameter	Quantity	Engine idle	Full engine load	Full load of injectors	Injector division capacity	Micro-doses
Average value	Volume [mm^3]	0.0647	0.2715	0.1786	0.1502	0.008
	Pressure [MPa]	2.667	5.376	5.468	5.671	0.863
Standard deviation	Volume [mm^3]	0.0004	0.0012	0.0007	0.0011	0.0012
	Pressure [MPa]	0.027	0.078	0.117	0.12	0.067
Difference between the highest and lowest value	Volume [mm^3]	0.0013	0.0036	0.0018	0.0032	0.0031
	Pressure [MPa]	0.078	0.23	0.339	0.353	0.179
Coefficient of variation	Volume [mm^3]	0.69	0.43	0.42	0.72	6.24
	Pressure [MPa]	1.02	1.451	2.143	2.116	7.806
Control time/pressure duration * 100%		72	72	62	60	89

Analyzing Table 8, it is evident that under full engine load conditions, the fuel pressure in the rail was 40% higher than the pressure observed during the injector division test. Despite this, the fuel pressure in the indicator measuring section during the full injector load measurement series was lower than during the injector division test.

For both fuel volume and pressure, the standard deviation was smallest at engine idle speed. For the volume of injected fuel, this parameter was similar across the full engine load, injector division capacity, and microdose measurement series. These three measurement series were also characterized by the largest difference between the maximum and minimum values of the injected fuel volume.

The ratio of the injector solenoid coil power supply time to the pressure duration in the indicator measuring section was highest for microdoses and lowest during the injector division test. This indicates that at a high injector operating frequency, a significant portion of the solenoid coil power supply time (in this case, 40 %) was not used for fuel injection into the indicator measuring section but was instead consumed by the injector opening process itself.

The present study was conducted using a completely new fuel injector. Based on the results obtained under these initial conditions, it is reasonable to hypothesize that, with continued operation and progressive wear of the injector, the repeatability of fuel delivery may deteriorate. This phenomenon merits further investigation in subsequent research efforts.

The ratio of the injector's actual opening time to the solenoid valve coil feed time significantly impacts the precision of fuel dosage. The actual opening duration of the injector is always shorter than the solenoid valve coil feed time, primarily due to the inertia of the injector's moving components. The greater the inertia of these components, the greater the discrepancy between these two durations. Inertia forces acting on the moving parts inside the injector cause delays in both opening and closing the injector. As a result, the fuel injection process ends later than the engine controller assumes. For small injection rates, this time discrepancy becomes critical, as such deviations can lead to undesirable variations in fuel dosage.

For short injector opening times, the time required to open and close the injector accounts for a large proportion of the total opening duration, leading to high dosing variability. This issue becomes less significant as injector opening times increase. The inertia of the injector's moving parts can affect dosing repeatability differently depending on engine load. For example, low injection pressure can extend the injector opening time due to reduced force acting on the injector needle, which influences the proportion of the aforementioned durations.

The high inertia of the moving components inside the injector is one of the most significant factors affecting the emission of toxic exhaust components in compression ignition engines. Uncontrolled injector dosing during low injection rates, when dosing variability is highest, can increase the concentration of toxic exhaust components such as nitrogen oxides and particulates. Addressing the issue of fuel dosing variability is therefore crucial for developing more precise injection control algorithms and improving injector design. These improvements will help engines comply with increasingly stringent emission standards.

To mitigate issues related to dosing variability under conditions of low injection pressure and short injector opening times, the use of more efficient engine control electronics with higher sampling frequencies should be considered. This enhancement would reduce the control system's response delay to signals from engine sensors. Specifically, it would enable a faster response of the engine controller to uneven angular accelerations of the crankshaft during the operating stroke of each cylinder. Such improvements would allow for quicker and more accurate corrections to the solenoid injector coil's control signal, ensuring high fuel dosing repeatability under all operating conditions.

An effective way to improve the repeatability of fuel dosage by electromagnetic injectors is to optimize the injector design. This can be achieved by using lighter materials for the injector's moving parts. As is well known, one of the challenges with electromagnetic injectors is the high inertia of the moving parts, which causes delays in the injector's opening and closing phases. The use of titanium can help mitigate this issue due to its low density and high strength, as titanium is approximately 40% lighter than metal alloys with similar properties.

Another approach to enhancing injector performance in terms of dosing repeatability is to improve the solenoid valve itself. This involves increasing the solenoid's strength to accelerate the solenoid anchor's movement, allowing the control chamber valve of the injector to open more quickly. Additionally, it would be necessary to develop algorithms to adapt the waveform of the solenoid valve control signal to the engine's operating conditions, tailoring the signal to the current engine load. These improvements would enable better control of the injector's opening and closing phases.

Further advancements in electromagnetic injectors remain justified. While piezoelectric injectors have largely replaced electromagnetic injectors in some applications (e.g., passenger cars), electromagnetic injectors continue to be widely used in the automotive industry. For example, HADI (Hydraulically Amplified Diesel Injector) systems, based on electromagnetic injectors, have been utilized in trucks since 2011. Given the extensive use of trucks in transportation and their larger engine displacements compared to passenger cars, further development of electromagnetic injectors aimed at increasing dosage repeat ability is worthwhile. These injectors continue to play a critical role in the automotive sector.

The study provided valuable insights into the relationship between the injector's actual opening time and the timing of the solenoid valve coil supply. The findings illuminate the mechanisms influencing fuel dosage variability, particularly for short injector opening times and low injection pressures. This knowledge can inform the design of new, more precise injectors and enhance injection control algorithms. Understanding how the proportions of actual injector opening time and solenoid valve coil supply time vary with engine load conditions could be incorporated into control algorithms, reducing fuel dos age variability. Moreover, the study identifies the specific conditions under which dosage non-repeatability is most pronounced, offering practical guidance for future research and development.

Continued research into fuel dosing variability is essential to expand knowledge in this area. One promising avenue of research is to analyze the impact of injector design changes – for instance, examining how the diameter or number of nozzle holes affects dosing repeatability under different conditions. Additionally, studying the effects of materials used for the injector's moving parts could help determine how their masses influence the injector's opening and closing dynamics, and thus fuel dosage repeatability. Computational Fluid Dynamics (CFD) simulations could also be employed to investigate fuel flow dynamics, providing a deeper understanding of how fluid flow characteristics within the injector relate to the repeatability of small injection doses. Another area worth exploring is the effect of alternative fuels and their blends on the injection process, addressing whether fuel type can enhance dosage repeatability and improve combustion quality.

6. Conclusion

It should be noted that the results of this research and the conclusions drawn below apply exclusively to electromagnetic injectors of the Common Rail system.

1. The use of the above-mentioned test stand to achieve the study's objectives did not compromise the validity of the conclusions, as the study was analytical and comparative in nature. Any numerically determined fuel injection parameters differing from actual values would differ consistently, i.e., they would be overstated or understated by the same amount. This consistency ensures that parameters such as the coefficient of variation remain unaffected, preserving the scientific value of this research.
2. The repeatability of the electric current intensity run controlling the solenoid valve coil is very high. Deviations observed on the falling edges of the current run are negligible and do not significantly affect injector operation or fuel dosing repeatability. This insight can be valuable for system diagnostics. Considering that each signal path supplying the solenoid valve coil under steady state conditions is identical, an increase in signal non repeatability would indicate damage to the engine control system rather than a fault in the injector.
3. The fuel injection time exceeds the solenoid valve coil control time due to the emptying and refilling of the control chamber during the injector's opening and closing processes. These actions require a specific amount of time, independent of the ECU (Electronic Control Unit) system. To compare the durations of the solenoid valve coil control period and the pressure maintenance period, the ratio of injector control time to pressure maintenance time was calculated and expressed as a percentage. The largest differences (60%) between these times occurred during high frequency injector operation (injector division capacity), while the smallest differences (89%) were observed during microdose implementation. This indicates that at higher injection frequencies, a significant portion of the control time is devoted to the injector's opening and closing processes. Knowledge of the dynamics of fluid flow in the injector control chamber and its impact on injector processes can be applied to optimize common rail systems using alternative fuels. The flow dynamics depend on fuel properties, which vary significantly for alternative fuels.
4. The lowest repeatability was observed in the pressure run during microdose implementation. Significant differences were noted in both the maximum pressure values and the injected fuel dose volumes. The coefficient of variation reached its highest values in this context: 6.24% for the injected fuel dose volume and 7.80% for the configurable control of the maximum pressure value. Such variability underscores the advantages of piezoelectric injectors, which enable more precise fuel dosing over shorter intervals. Based on the results, it can be concluded that the tested electromagnetic injector would not meet the requirements of current exhaust emission standards.
5. Across all characteristic operating points of the injector, the coefficient of variation for maximum pressure values was consistently higher than that for injected fuel volume. This discrepancy arises due to pressure wave phenomena in the fuel rail, high-pressure pipe, and injector itself. This study highlights the scale of wave phenomena issues within the high-pressure circuit and may encourage injection system designers to consider incorporating pressure wave damping devices into more advanced fuel rail designs.
6. Further work on improving fuel dosing repeatability is highly recommended. Greater dosing repeatability enables more precise control of injection volumes, offering the potential to increase the number of injection phases or divide existing phases, such as splitting a pilot dose into two smaller doses.
7. The developed methodology facilitates research into various aspects of fuel injection, including the effects of different injection strategies on dosing repeatability or the influence of alternative fuel properties. Research using this methodology could contribute to the development of fuel supply systems and injection control algorithms optimized for specific alternative fuels.
8. Shorter injector opening times amplify the impact of the inertia of the injector's moving components on fuel dosing consistency. Similarly, lower injection pressure reduces the forces acting on these components, further diminishing dosing consistency. These factors highlight the importance of addressing injector design and operating conditions to improve fuel dosing precision.

Acknowledgements

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Nomenclature

CFD	computational fluid dynamics
CI	compression ignition
ECU	engine control unit
HADI	hydraulically amplified diesel injector
IMA	Injektor Mengen Abgeleich
NO_x	nitrogen oxides
PWM	pulse width modulation
STPiW	stanowisko testowania pomp i wtryskiwaczy

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