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Evaluation of changes in fuel delivery rate by electromagnetic injectors in a common rail system during simulated operation

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Highlights

- A high-intensity operation of electromagnetic injectors used in CR systems is simulated.
- Changes in fuel delivery rate by the injectors during the simulated operation are determined.
- Changes in the surface texture of fuel injectors control parts are evaluated.

Abstract

The objective of this study was to determine changes in fuel delivery rate by common rail system injectors during their simulated operation on a test stand. Four Bosch injectors used, among others, in Fiat 1.3 Multijet engines were tested. The injectors were operated on a test rig at room temperature for 500 hours (more than 72 million work cycles). During the test, pressure and injection frequency were changed. Changes in the operating parameters were estimated based on obtained injection characteristics and effective flow area determined thereby. The observed changes in fuel delivery rate were compared with results of the surface analysis of control valves and nozzle needles. Despite the stated lack of wear, significant changes in the dynamics of injector operation were observed, particularly at short injection times. Small pilot injections cannot be corrected by the fuel injection control system because they do not affect the changes in torque; however, they do affect the combustion process. This creates conditions for increased emission of toxic exhaust components.

Keywords

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common rail, fuel delivery rate, injector operation.

1. Introduction

An internal combustion engine is currently the most widely used source of power for road transport. Given more and more demanding requirements for the emission of harmful exhaust components, engineers are striving to improve the combustion process in order to ensure the lowest possible emissivity and the highest possible thermal efficiency [28]. The fuel injection process and its control play a very important role in this respect [1, 5, 11].

Currently, compression ignition engines predominantly use common rail fuel injection. The design of such system makes it possible to minimize inaccuracies of fuel injection resulting from inertia of the injection system components, which is typical of systems based on injection pumps. Fuel pressure in the end part of the common rail system, i.e. the area between injectors and a high-pressure pump, is maintained at the same level, which allows for maintaining the same operating conditions for all engine cylinders. Since fuel is injected in several doses, it is possible to obtain the desired fuel distribution in the cylinder, which allows for the control of the combustion process and thus reduced emission of toxic exhaust gas components and lower pressure rise rate [22, 27]. However, this requires high precision of fuel metering and maintenance of constant fuel delivery rate characteristics during operation. The combustion process is particularly sensitive to fuel injection process and pilot injection quantity [9],

therefore the metering of small fuel quantities in the ballistic regime for injector needles requires high precision.

Common rail fuel injection systems are often associated with various types of operational malfunctions. These predominantly result from damage of the injection system components, i.e. a high-pressure fuel pump or – more frequently – injectors. Injector damage is usually caused by poor quality of fuel [30, 31, 33] or cavitation erosion related to rapid flow of fuel through the injector [2, 13, 14, 32]. Poor fuel quality usually leads to accelerated accumulation of deposits; it can also accelerate erosive wear if fuel contains fractions with low vapour pressure.

Birgel et al. [3] reviewed the literature on the mechanisms of deposit formation and their effect on injector characteristics. Research has shown that fuel flow rate across the injector decreases linearly during operation, resulting in a corresponding reduction in engine power. Following 30 hours of engine operation at full load, the fuel delivery rate was reduced by about 3.5%. The literature review shows that many studies focus on the influence of biocomponents on deposit formation [15, 17]. In general, biofuels induce the formation of hard polymers inside the injectors and of carbon deposits around the injector holes. Hofmann et al. [7] investigated the effect of worn injectors on changes in control system signal characteristics, namely the needle lift and the fuel pressure in the feed line. It was found that a worn injector – its mileage unknown – had the needle lift reduced

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by about 20% compared to a new injector. A similar trend was observed with respect to the fuel delivery rate. The reduced needle lift and fuel flow rate were attributed to the formation of hard deposits. However, the authors observed that the reduced needle lift during operation is to some extent compensated for by cavitation wear of the injector holes.

Apart from deposit formation and cavitation erosion, the problem of tribological wear of injector components is often discussed in the literature too, especially in terms of alternative fuels. However, it should be emphasized that the available studies mainly concern older generation injection systems operating at pressures being an order of magnitude lower than those in common rail systems. Obtained results are not unequivocal, predominantly due to the limited time of the studies. Although visible changes in the surface profile are observed, they are not regarded as having direct impact on operating parameters of the fuel injection system components [25]. With good lubrication, geometrical changes in the interacting injection system components are negligible. The study conducted by Niewczas et al. [20] showed that after the durability test of 60 million cycles, the plunger diameter in the injection pump increased by about 4 μm .

Schuckert et al. [29] investigated the relationship between injector aging and fuel delivery rate. The results showed that reduced cross section of the injector holes due to deposit formation does not necessarily lead to reduced fuel delivery rate at short injection times. Hydraulic phenomena cause the injection time to be longer at the same energizing time, thus compensating for the lower fuel flow rate. Payri et al. [24] quantified the closing hydraulic delay of a piezoelectric injector. The aged injector was characterized by an increased fuel flow rate than the new injector for the same energizing time.

Optical analyses of fuel spray conducted by Hofmann et al. [7] showed that the reduced injector hole make the fuel spray narrower and increase its range, while the larger diameter holes have the opposite effect. Pielecha et al. [26] conducted a comparative analysis of fuel spray characteristics for new and aged injectors. Following a mileage of 80,000 km, the worn injectors were characterized by 30% reduced cone angles. A slight increase in the spray range was observed too. The above changes in fuel spray geometry indicate reduction in the cross section of the holes during operation.

Recently, Payri et al. [23] investigated the effects of injector aging on multiple injection strategies. The injector was subjected to wear on a test rig under controlled conditions. The researchers quantified the observed changes in the fuel flow rate in the injector, attributing them to reduced hole diameters. Similarly to Schuckert et al. [29], they found that increased injection timing is significant and that multiple injection leads to continuous fuel flow, as in the case with single injection.

Research has also shown that even new injectors differ significantly with respect to their flow characteristics. Ferrari et al. [4] determined the characteristics of fuel injection rate depending on the injection timing for different pressures in the fuel rail. Results obtained for the tested injectors showed that at short energizing times typical of pilot injection, the spread of injected fuel quantity is greater than the mean value. Changes in the injection characteristics and injection rate have a direct impact on the combustion process in the cylinder. The pilot injection quantity is of particular importance [8], and small fuel quantities are particularly exposed to variability resulting from wear and geometrical changes of the injectors.

Hofmann et al. [6] proposed an algorithm for injection strategy correction to compensate for changes resulting from injector aging. A simplified model of injection and combustion was sufficient to select optimal injection strategies. Importantly, the study found that a mere change of the injection time is not sufficient to compensate for changes in its characteristics, due to the fact that apart from the fuel flow coefficient, the spray characteristics and dynamic parameters are changed too. Nevertheless, in the study, only changes in the cross section of the holes were considered to be an indicator of wear.

The literature review shows that, on the one hand, detailed data are available about tribological processes and the relationship between technical condition and injection characteristics; on the other hand, however, the actual changes in fuel delivery rate characteristics are unknown. These gaps in knowledge result from the fact that the assessment of changes in the operating characteristics of injectors requires long-term studies under controlled conditions. In real operating conditions, simultaneously occurring processes, such as abrasive wear and internal deposits formation or cavitation wear of injector holes and carbon deposits formation, can compensate each other.

The objective of this study was to determine changes in injection characteristics of the analysed injectors following a high-intensity 500-hour laboratory durability test, amounting to a mileage of approx. 70,000 km. As a result, it was possible to determine the extent of changes in the injector characteristics during the run-in period. Tests were conducted at room temperature, which reduced, among others, the formation of internal deposits. In effect, it was possible to isolate the effects related only to tribological wear. The changes in injection rate characteristics were compared with changes in the surface texture of key elements of the injectors.

2. Simplified description of fuel injection process

In common rail systems, fuel quantity metering is adjusted by changing injector valve opening time. Theoretically, fuel flow through an open valve is steady and results from the fuel nozzle cross section and fluid velocity:

$$\dot{m}_{th} = \rho_f A_0 v_{th}, \quad (1)$$

where ρ_f is the fuel density, A_0 is the total cross-sectional area of the injector nozzle openings, and v_{th} is the theoretical flow velocity of fuel across the injector tip. The flow velocity is derived from the Bernoulli equation:

$$v_{th} = \sqrt{\frac{2\Delta p}{\rho_f}}, \quad (2)$$

where Δp is the difference between the pressure of injected fuel and the pressure across the area into which fuel is injected. However, the actual flow rate is corrected by the flow coefficient μ , defined as the ratio of actual to theoretical mass flow:

$$\mu = \frac{\dot{m}}{\dot{m}_{th}}. \quad (3)$$

Based on Equations (1) and (2) and taking into account the coefficient μ , the actual mass flow rate can be expressed as:

$$\dot{m} = \mu A_0 \sqrt{2\rho_f \Delta p}. \quad (4)$$

For convenience, the actual fuel spray cross section can be presented as the product of the geometric cross section of the valve and the flow coefficient. Additionally, by introducing the injector opening time t_r , based on the measured fuel volume V corresponding to one fuel injection, the actual cross section of the fuel spray can be calculated as:

$$\mu A_0 = \frac{V}{\sqrt{2\frac{\Delta p}{\rho}} t_r}. \quad (5)$$

However, the actual injector valve opening time in Equation (5) is not the same as the theoretical energizing time of the solenoid injector. The delay in injector opening results from a curve of inductor current increase, mechanical resistance, hydraulic resistance and inertia of both the fluid and the injector mechanical components. The delay occurs at injector closing too, due to the above reasons. It is worth noting that the delay values are so large that at short energizing times, the physical injection begins after the end of electric pulse [16]. Assuming that the delays are independent of the injected fuel quantity, the total difference Δt between the energizing time ET and the actual injection time t_r can be determined by analysing injection rate characteristic (Fig. 1). The intersection of the linear regression line with the abscissa indicates the time at which the theoretical injection rate is equal to zero. This time is the difference between the valve opening delay and the valve closing delay. Therefore, knowing the injection rate characteristics for a specific type and pressure of fuel and solenoid timing parameters, the actual injection time can be estimated based on the following dependence:

$$t_r = ET - \Delta t . \quad (6)$$

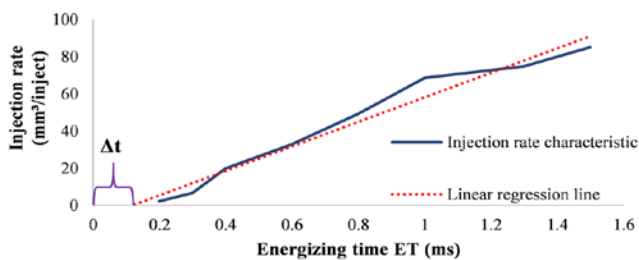


Fig. 1. Injector dead time determined based on injection characteristics

3. Research methods

Bosch high-pressure electromagnetic fuel injectors applied in common rail fuel injection systems were used in the study. Four injectors of the same type (0445110183) were tested. Laboratory tests were carried out on a test rig for testing fuel injection pumps and fuel injectors, STPiW-3, manufactured by Autoelektronika Kędzia (Fig. 2).

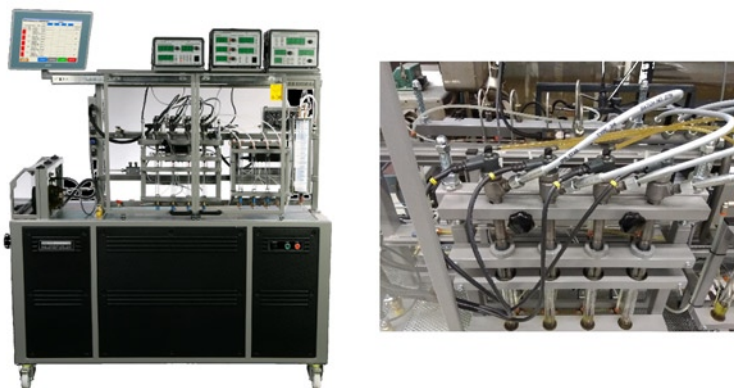


Fig. 2. STPiW-3 test rig for testing fuel injection pumps and fuel injectors

The injectors were operated for 500 hours, which amounted to about 72.18 million work cycles. To simulate operation of the injectors under conditions reflecting the real ones, the injection pressure and injection frequency were changed during the test. Detailed information about the experimental parameters is given in Table 1.

The fuel used in this study was Ekodiesel Ultra diesel oil produced by PKN ORLEN (Poland), the standard properties of which are given in Table 2. To ensure the same properties of the fuel, its temperature was stabilized at $40 \pm 2^\circ\text{C}$.

Table 1. Parameters of performance tests

Work time (h)	Total work time (h)	Injection pressure P_{rail} (MPa)	Injection frequency (Hz)	Share in the test* (%)
120	120	100	25	15
30	150	120	35	5
150	300	120	40	30
130	430	120	50	33
70	500	140	50	17

* share in the test denotes the percentage number of injections made under given operating conditions to the overall number of injections made by the injector during the test.

Before and after the performance test, volumetric injection rate characteristics were determined. Conditions applied in the test are listed in Table 3. They were selected in such a way as to cover most operating conditions occurring in real conditions, i.e. low, medium and high injection pressures, as well as short and extended injection timing. The longest injection times of 1.5 and 2 ms were selected for the test due to the fact that they ensure a long period of stable mass flow rate, thanks to which it is possible to accurately determine the flow coefficient for the injector. All combinations of the variables were tested, yielding a total of 100 measurement points. The measurements were repeated five times, and based on obtained results, the average injection rates were calculated for every measurement point.

After the durability test, the injectors were tested on a specialized test bench EPS 945 from BOSCH, which is used for testing and issuing correction codes in accordance with the procedure specified by the manufacturer. Obtained changes in the injection rate were evaluated in terms of statistical significance. The evaluation was performed using Statistica 13.0. Since statistical features of the obtained results (distribution and variance in individual tests) precluded the use of parametric tests, the Wilcoxon signed-rank test was used instead. The level of statistical significance was set at $\alpha = 0.1$, which corresponds to the values used in technical sciences [12].

After that, the injectors were disassembled and topographically examined using the Alicona InfiniteFocus5G optical device for surface roughness and texture measurements. Surface roughness was measured in two stages. First, a 3D model was created using the InfiniteFocus technology. Next, a surface profile was extracted from the 3D model, and – on the basis of this profile – roughness parameters were calculated in compliance with ISO standards. In this way, it was possible to identify changes in the surface of key elements of the injectors, i.e. control valves and injector needles.

4. Results and discussion

In accordance with the assumptions of the experiment, changes in injector operation were evaluated predominantly based on the changes in their injection rate. Fig. 3 shows the characteristics of injection rate for selected parameters of their operation from the values given in Table 3.

An analysis of the above injection rate characteristics demonstrates that in almost every case, regardless of the injection pressure, the injection rate decreases during the test. A decrease in slope of the injection rate characteristics curve in relation to the horizontal axis of the graph, in accordance with the scheme shown in Fig. 1, indicates changes in the effective cross-sectional area of the injector, as illustrated by the characteristics shown in Fig. 4.

An analysis of the behaviour pattern of the effective cross-sectional area of the injector demonstrates that this parameter undergoes significant changes in the entire range of measurement points. Statistically significant changes can be observed for the average value of the effective cross-sectional area of the injector. According to the statistical test results, the value of p is 0.086 for Injector I, while for Injectors

Table 2. Standard physical and chemical properties of the fuel used in the study, according to the data provided by the manufacturer

Property	Unit	Specifications		Test
		Lower limit	Upper limit	
Cetane number	-	51.0	-	PN-EN ISO 5165
Cetane index	-	46.0	-	PN-EN ISO 4264
Density at 15 °C	kg/m ³	820.0	845.0	PN-EN ISO 12185 PN-EN ISO 3675
Flash point	°C	56.0	-	PN-EN ISO 2719
Carbon residue (on 10% distillation residue)	%(m/m)	-	0.30	PN-EN ISO 10370
Ash residue	%(m/m)	-	0.010	PN-EN ISO 6245
Water content	mg/kg	-	200	PN-EN ISO 12937
	%(m/m)	-	0.020	
Oxidation stability	g/m ³	-	25	PN-ISO 12205
	h	20.0	-	PN-EN 15751
Lubricity, corrected wear scar diameter (wsd 1.4) at 60 °C	mm	-	460	PN-EN ISO 12156-1
Viscosity at 40 °C	mm ² /s	2.000	4.000	PN-EN ISO 3104

Table 3. Injector parameters used for determination of injection characteristics

Parameter	Tested values
Injection pressure, p_{rail} (MPa)	30; 40; 50; 70; 80; 90; 100; 120; 150; 170
Nominal injection time, ET (ms)	0.2; 0.3; 0.4; 0.6; 0.8; 1.0; 1.3; 1.5; 1.8; 2.0

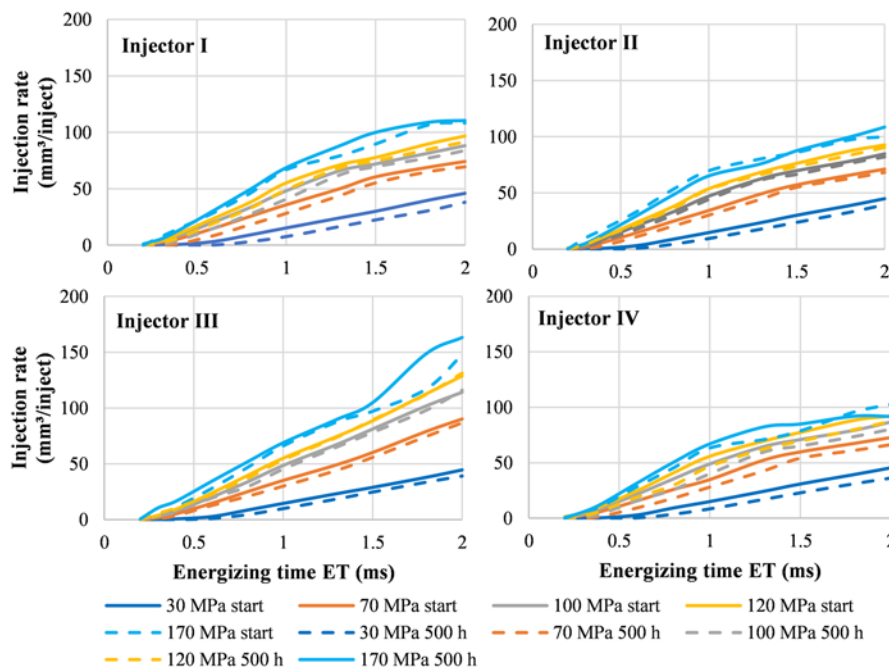


Fig. 3 Injection rate characteristics of the tested electromagnetic injectors

II, III and IV $p < 0.001$. Regarding Injector III, the average value of the coefficient has increased, while in other cases its average value decreased. This has a direct impact on the operation of the injectors, because injection rate control is based on injection timing control with

the assumed pressure values and the injection rate obtained thereby. If the injection process itself is changed, it leads to deterioration of the internal combustion engine operation, regardless of whether the obtained flow rate is higher or lower than the reference value. This may cause changes in the achieved engine operating parameters, as well as lead to increased emission of toxic exhaust gas components, predominantly nitrogen oxides and solid particles [19, 21]

In addition, following the performance test, the injectors were tested on the BOSCH EPS 945 test stand. The test has shown that Injector IV neither meets the assumed requirements, nor it is not possible to correct its injection characteristics and thus requires mechanical intervention. As for the other injectors, despite significant changes in their injection rates (Fig. 3), particularly at short injection times, they meet the manufacturer's standards and can therefore be qualified as operational.

An attempt was also made to establish a relationship between the changes in the injector operating characteristics and the surface condition of the interacting injection system components. The literature review shows that the injection rate can be affected not only by the holes but also by wear of the surfaces of the injection system components responsible for the fuel injection process, i.e. the conical surface of the control valve interacting with the valve ball and the surface of the injector needle interacting with the injector tip body [2, 10, 18]. After the performance test, these components were subjected to surface texture examination. Surface examination results obtained for the control valves are shown in Fig. 5 and for the injector needles in Fig. 6.

An analysis of the images in Figures 5 and 6 showing the surface texture of the fuel injector control components demonstrates that no surface degradation took place during the performance test, which means that no component has been damaged or lost its operational ability. Evaluation of this type is usually made by microscopic examination aimed at identifying visible surface defects. The images of the sur-

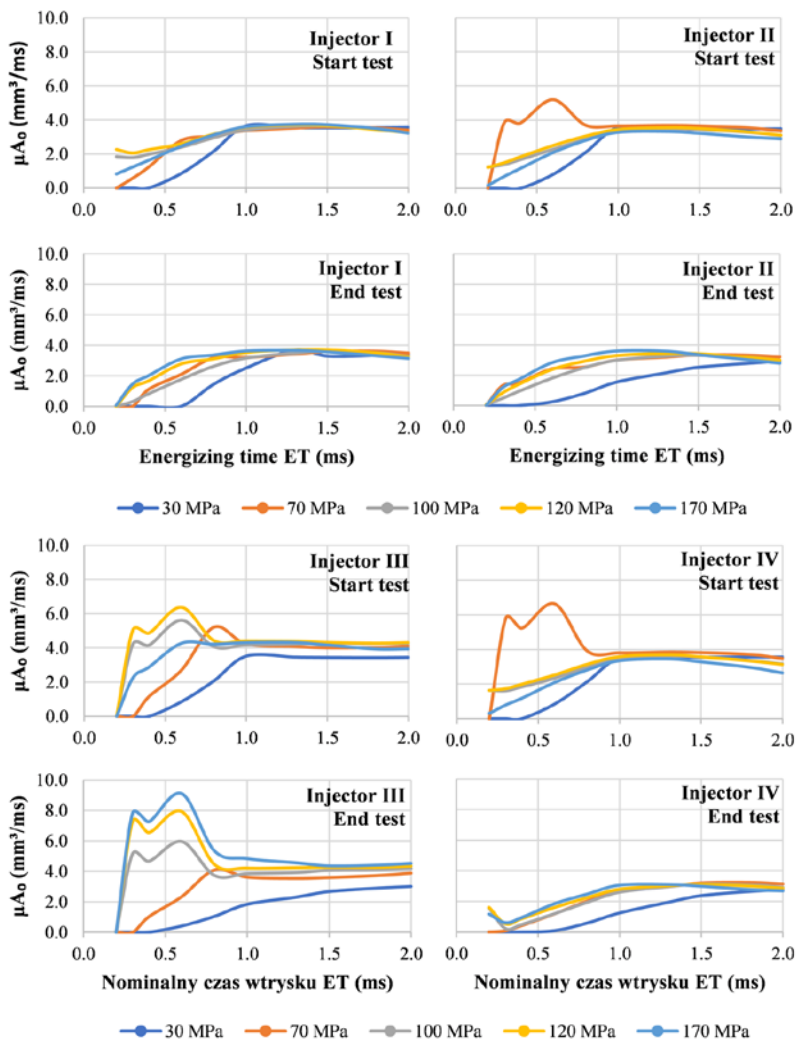


Fig. 4. Characteristics of the μA_0 coefficients μ and A_0 of effective cross-sectional area of the injector

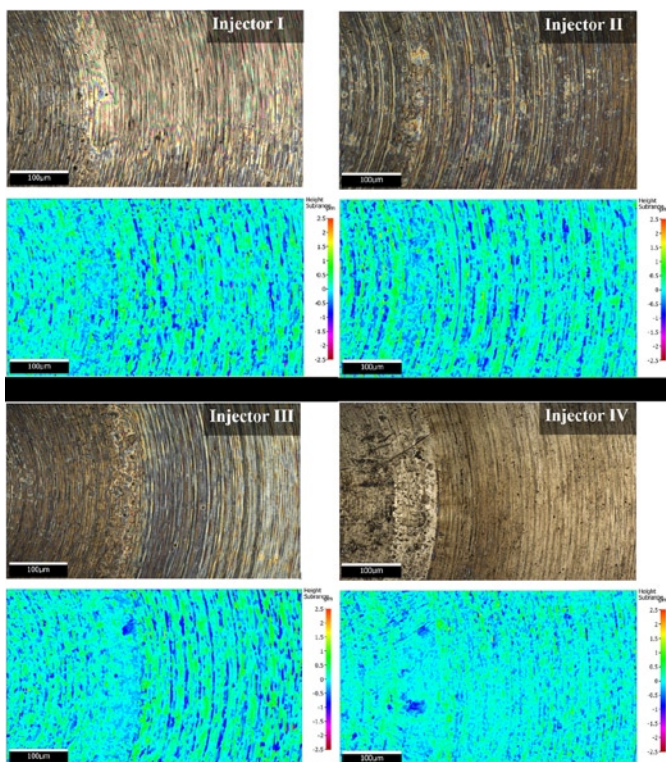


Fig. 5 Images showing the surface texture of control valves

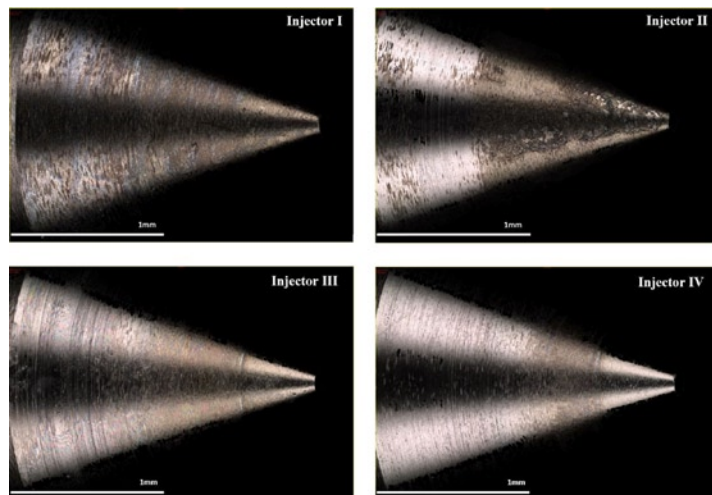


Fig. 6. Images showing the conical surface of nozzle needles

faces of both control valves and injector needles show no visible damage.

An analysis of the surface texture of the control valves was performed in the area of interaction with the valve ball, and obtained results are given in Table 4. An analysis of the Abbott-Firestone curve for the examined surface does not indicate significant degradation of the surface. No increase in the parameters V_{vc} (core void volume) and V_{vv} (valley void volume) is observed with respect to the valve that was not subjected to performance tests. Similarly, the behaviour pattern of the S_v parameter (the maximum pit height) does not indicate any damage.

A comparison of the flow characteristics and surface condition of the interacting components reveals that wear processes are not the main cause of changes in the fuel delivery rate. Given the moderate temperature during the tests, the effect of polymeric deposits can be excluded, too. This is evidenced by insignificant changes in the flow coefficient in the range of long injection times. On the other hand, considerable changes in the flow parameters can be observed in the range of short injection times. This means that in the initial stage of operation, the friction of the interacting components changes to a large extent, which affects the dynamics of the pilot valve and injector needle. As a result, small pilot injection quantities can vary greatly during operation and be different for different cylinders.

It should be emphasized that such changes in injection characteristics may be undetected and thus non-compensated for by adaptive algorithms, as the injected fuel quantities are small and do not significantly change the torque. On the other hand, changing the pilot injection significantly affects exhaust emissions. Unfortunately, the observed changes in fuel injection characteristics are quite incidental. The injectors tend to both increase and decrease small fuel quantities. The relationship between fuel pressure and injection rate char-

acteristics is also ambiguous. This proves that the injector operation dynamics depends on many factors. Given the multidirectional nature of the observed changes, it is not possible to develop an injector wear model that could be used to modify the injection strategy.

Table 4. Surface texture parameters of the control valves subjected to performance testing

Parameter	New valve	Valve of Injector I	Valve of Injector II	Valve of Injector III	Valve of Injector IV
V_{vc} (ml/m ²)	0.486	0.354	0.386	0.244	0.291
V_{vv} (ml/m ²)	0.055	0.040	0.043	0.042	0.0291
S_v (μm)	2.32	1.98	2.04	2.03	2.02

5. Conclusions

In this study, a 500-hour performance test of electromagnetic fuel injectors for a compression-ignition engine was performed. The test was carried out on a test stand by simulating real operating conditions. It was conducted at room temperature to minimize the formation of deposits inside the injectors. Before and after the durability test, injection rate characteristics were determined. Additionally, the changes in the surface texture of the cooperating pairs were evaluated. Based on the results obtained in this study, the following conclusions can be drawn:

- In all tested injectors, statistically significant changes were observed with respect to the effective cross-sectional area of the flow coefficient. However, the direction of these changes differed. For three of the tested injectors, the effective cross-section decreased, but it increased for one of them.
- The examination of the surface of the injector needles and control valves did not reveal any visible damage that could affect the injection process. In addition to that, no significant changes in the texture of their working surfaces were detected.

- Despite the stated lack of wear, the dynamics of injector operation changed to a significant extent. Specifically, there occurred changes in the effective cross-sectional area of flow at short injection times when the valve opening and closing delays play a decisive role, because a stable flow state is not achieved.
- To compensate for the changes in injector operation dynamics, which are important in metering pilot injections, it is necessary to obtain information about every fuel quantity in multi-stage injection. This information can be indirectly obtained by individual measurements of fuel pressure in each of the injectors.

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