INTERNATIONAL JOURNAL OF AUTOMOTIVE AND MECHANICAL ENGINEERING
ISSN: 2229-8649 e-ISSN: 2180-1606
VOLUME 22, ISSUE 3, 2025, 12614 - 12626
DOI: https://doi.org/10.15282/ijame.22.3.2025.6.0963

UNIVERSITI MALAYSIA PAHANG
AL-SULTAN ABDULLAH

RESEARCH ARTICLE

Influence of Wear on Precision Pair Components in Modern Fuel Injectors on the Operating and Environmental Performance of a Compression-Ignition Engine

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ABSTRACT – The paper discusses issues related to wear phenomena occurring in modern compression-ignition engine fuel supply equipment. The paper examines how non-efficient injectors affect the operating and environmental performance of a common-rail diesel engine. Engine and laboratory tests were carried out. During the engine tests, power, torque, specific fuel consumption (SFC) and environmental parameters were measured on a bench for the engine running on non-efficient and efficient fuel injectors. Wear of injectors resulted in a decrease in engine power of up to 9% and a decrease in engine torque of up to 2%. In contrast, SFC increased for the worn injectors by more than 9%. The non-efficient injectors were then examined on an STPiW-3 test bench with a thermal imaging camera to determine their degree of wear. They were then disassembled into their component parts and examined with a stereoscopic and an electron microscope. The examinations showed that there was contamination inside the fuel injectors tested, both from outside and generated by the high-pressure pump. It is discussed how the inadequacies of the injection apparatus affect the combustion process of the combustible mixture in the cylinder headspace and the overall operation of the engine.

ARTICLE HISTORY
Received : 10th Mar. 2025
Revised : 30th June 2025
Accepted : 18th July 2025
Published : 01st Sept. 2025

KEYWORDS
Fuel injector
Precision pair
Fuel contaminants
Fuel atomiser
Common-rail system

1. INTRODUCTION

Modern compression-ignition engines are equipped with electro-hydraulic common-rail fuel supply systems, which allow the injection dose to be divided into several stages (pilot, main and afterburning dose) [1]. This affects the formation of the combustible mixture and the parameters of the fuel injection into the engine combustion chamber. The aim of introducing this type of solution was to optimise the combustion process taking place in the engine compartment in order to comply with modern emission standards. Fuel is introduced into the combustion chamber by means of fuel injectors. The fuel flowing out of the injectors breaks down into a collection of droplets that form a spray pattern with a complex internal structure. Fuel injection parameters can be classified into qualitative and quantitative [2]. Qualitative ones include the range, angle of dispersion, atomisation and velocity of the fuel jet, while quantitative ones include the volume of the injected liquid. These parameters are mainly influenced by the degree of wear of the needle and nozzle tribological associations, and the fuel injector and piston control valve. The fuel injector is mounted in the engine head directly in the combustion chamber of the engine. Its operating conditions are severe due to the high pressures and temperatures prevailing inside its body and in the engine combustion chamber itself.

As a result of the operation of the engine, its components are subject to various wear processes such as cavitation, erosion, corrosion or abrasion (see Figure A1 in Appendix A). Compression-ignition engine fuel also has a lubricating function [3,4], and its quality is therefore very important in the processes taking place in precision vapour associations. The parameters determining the lubricating properties of fuels are viscosity and density. Factors influencing the viscosity value of a liquid include the size and type of particles of which it is composed, and their spatial distribution. Pressure and temperature are also factors that influence viscosity. An increase in the pressure of a liquid causes the particles to move closer together and intermolecular interactions to increase, which increases viscosity. A linear increase in viscosity occurs up to a pressure of 25 MPa in the system, after which viscosity increases exponentially. With increasing temperature in liquids, the distance between particles increases, which is equivalent to a decrease in interaction and viscosity. Impurities in the form of other liquids reduce viscosity. In addition, the fuel may contain solid, externally sourced and organic deposits resulting from the ageing process.

The wear of injection equipment components progresses in a non-linear manner [5], meaning that the more the component is worn, the faster it wears out. This is caused by an increase in pressure during fluid flow in the precision vapour components and an increased temperature in this area. The temperature rise is caused by the increased pressure of the leaking component. This adversely affects the other parts of the injector and causes them to wear even faster. The increased temperature in the system also contributes to increased deposit formation throughout the system. Studies show that this applies to both compression-ignition and spark-ignition engine fuel supply systems [6]. The high-pressure pump also produces metallic filings of varying sizes from a few to several hundred microns during operation. The size of the metallic debris influences their quantity in the fuel system. The smaller they are, the more of them enter the fuel injectors,

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degrading them. The common-rail injection system in modern motor vehicles operates at operating pressures ranging from 25 to around 200 MPa, depending on the design. The task of the high-pressure pump is to dam up the fuel in the system, and the high and low pressure regulators adjust it to the required values. With such variable and high pressures, it is natural for metallic filings to form in the pump as a result of its operation. Their quantity and size are important, as this affects their spread throughout the system. One of the most vulnerable to accelerated wear is the fuel injector nozzle [7]. This component is responsible for the entire fuel atomisation process. The size of the fuel jet and the rate of fuel evaporation in the cylinder depend on its technical condition [8]. During operation, the temperature inside the atomiser increases, stabilises and remains constant. If the precision vapour on the firing pin is worn, an increase in temperature within it occurs. This causes changes in injection rates, especially at low system pressures, and wear of the injection holes [9]. The increase in temperature also favours the development of corrosion in the nozzle [10] and compromises the lubricating properties of the fuel [11]. Another factor affecting the service life of the fuel atomiser is the phenomenon of cavitation during fuel flow through it.

In common-rail systems, operating pressures reach up to 250 MPa [12] and fluctuate all the time. The fluid flow throughout the system is laminar at lower pressures and hyper-turbulent at maximum pressures. Such conditions favour the development of cavitation phenomena [13]. It should be remembered that the conditions inside the fuel atomiser and during the injection process itself, inside and outside the orifices, are different. In the atomiser, as well as in the whole system, there is a high pressure depending on the engine load, while during the injection process, according to the laws of fluid mechanics, the pressure is equal to that prevailing in the engine combustion chamber, while the fluid flow velocity is very high. Therefore, the occurrence of the cavitation phenomenon must be approached from two aspects. During the fluid flow inside the injection system, it is undesirable, but during the fuel injection process itself, it can contribute to improving the combustion process of the combustible mixture [13,14]. The occurrence of cavitation bubbles in the stream improves its atomisation. This speeds up the vapourisation process of the fuel and mixing with the air. This affects the auto-ignition delay period by shortening it. On the other hand, higher pressure in the common-rail system causes greater wear of the precision vapours on the injection pump pistons and in the fuel injectors. At higher pressure, there is a higher temperature. The viscosity of the fuel is reduced, which worsens the lubricity coefficient. As a result of these factors, metallic filings are formed in the injection pump, which, when they reach a sufficient size (a few microns), enter the entire system, destroying it.

It is possible to numerically model the cavitation phenomenon prevailing in the fuel atomiser [15,16]. This type of work relates only to phenomena occurring at the nozzle orifices. This is due to the fact that it is very difficult to model the entire fuel injector, as its exact dimensions are not known. The elements of the precision pairs, the working range of the valve and all other components are dimensioned to a few microns with respect to each other, so without a corresponding very accurate measuring apparatus, this process is impossible. It is possible to estimate the operating parameters of a modern injector, such as fuel injection rates, using artificial intelligence algorithms [17], treating the fuel injector as a black box model. The modern fuel injector is built with a body that contains two areas of the valve, which are responsible for controlling its operation, and a nozzle area, whose task is to organise the fuel spray [18]. It is difficult to study how the degree of wear of the precision pairs of key components affects the injection rates, as the degree of wear of the components is not measurable. Many research works determine the course of cavitation and erosion phenomena using Computational Fluid Dynamics (CFD) simulations [19–21]. A suitable algorithm makes it possible to detect changes in channel pressures in the fuel injector. This method can effectively estimate the phenomenon of cavitation erosion in the nozzle or valve and helps in the design of modern fuel injectors and the programming of their operating parameters.

Wear of the precision pair elements in modern fuel injectors leads to changes in their operating parameters, such as injection rates, return rates and fuel injection delay. The fuel injection delay parameter is the time from the coil or piezoelectric element of the injector under test to the start of the fuel supply process into the combustion chamber. Variations in these parameters affect the combustion process of the combustible mixture in the cylinder working space, resulting in increased toxic emissions during the process, increased fuel consumption and a deterioration of the engine's operational performance. The aim of this paper is to analyse how degrading phenomena in the fuel injector components affect their injection and overflow rates. The return or overflow dose is the discharge of working fluid during the operation of the injector. According to manufacturers' standards, overflow rates should oscillate between 20 and 25 mm^3/h. This means that a new injector at its maximum working pressure should drop around 20–25 mm^3 of fuel per one firing pin lift (duty cycle). This is influenced by the condition of the precision pairs and the valve sealant. If the overflow exceeds 50 mm^3/h, then the fuel injector should be repaired. The size of the overflow affects the injection rates. During the test of the fuel injectors, the full and medium load, pilot and freewheel doses are examined. These must be within a certain range during the test. If any of the doses are too high or low, the fuel injector is treated as inefficient. Wear of the precision pairs causes these doses to diverge, and it is difficult to adjust them. In this study, an engine running on inefficient fuel injectors was investigated. Atmospheric toxic emissions, fuel consumption and its operating parameters, such as power and torque, were analysed. The electromagnetic fuel injectors were then dismantled, a microscopic analysis of the precision pairs was carried out, the conditions under which they operated were determined, and how the wear of individual components affects their operating parameters was estimated. Non-efficient fuel injectors cause the engine to run improperly. Fuel consumption and toxic emissions into the atmosphere increase. In the next stage of testing, functioning fuel injectors were fitted, and the entire engine testing process was repeated. The results of the experiment are presented in the following paper.

The scientific relevance of this work is important, as it discusses an issue related to environmental protection and ecology. Research on modern vehicles is carried out when they are new and drive out of factories. Few studies examine how their wear affects the environment and the health of society. Wear processes in engine components can affect the emission of toxic substances into the atmosphere. Many vehicles that met emission standards when new may no longer meet them after several years of operation. In addition, by examining the state of wear of engine components and their impact on the environment, procedures can be introduced during periodic maintenance that will result in an appropriate response and replacement of critical components that will affect emissions throughout the vehicle's operating range.

2. METHODS AND MATERIALS

Experimental tests were carried out on a Fiat 1.3 JTD engine (Fiat, Turin, Italy) – see Table 1 – with an AMX 100 electromotor brake and an AMX 212 fuel consumption meter (Automex, Gdansk, Poland). A Capelec exhaust gas analyser (Capelec SAS, Montpellier, France) and a MAHA MDO 2 opacimeter (MAHA Group, Haldenwang, Germany) were used for the tests. The exhaust emissions were measured in accordance with EN ISO 8178-1 [22,23].

Table 1. Research engine specification

Engine	Fiat 1,3 JTD
Model year	2002
Number of cylinders	4
Engine power	50 kW
Engine torque	200 Nm
Injection system	CR Bosch
Fuel injectors	1st generation electromagnetic CR
Fuel high-pressure pump	CP1K
Max injection pressure	135 MPa
Number of injectors	2

The measurement error of the test equipment is approximately 5%.

The injection and overflow dose rate tests were carried out on an Autoelectronics STPiW-3 test bench (Automotive Training Centre 'Autoelectronics Kędzia', Poznan, Poland) [24]. The fuel injectors were subjected to the standard test procedure. They were then disassembled into their component parts (Figure 1) and were initially examined under a stereoscopic microscope, followed by a precision vapour contamination analysis using an electron microscope.

Figure 1. Components of the tested Bosch electromagnetic injector on which microscopic analysis was performed (1 - nozzle needle, 2 - control piston, 3 – valve)

The aim of the fine analysis was to examine the chemical composition of the contaminants inside the fuel injectors. This study was performed by scanning electron microscopy on a Hitachi SU-70 microscope (Hitachi, Chiyoda, Tokyo, Japan) using Energy Dispersive Spectrometry (EDS). The analysis was performed at an accelerating voltage of 15 kV or 30 kV and a beam current of approximately 5 nA. Images of the Backscattered Electron Image (BEI) type, with contrast dependent on chemical composition, and of the Secondary Electron Image (SEI) type, with contrast dependent on surface topography [25,26], were recorded. Solid contaminants from the injectors were sampled only from selected components located in the interior shown in Figure 1. Solid contaminants were sampled by washing the components in an ultrasonic cleaner in acetone and then filtering the liquid. In the next step, the resulting precipitate was applied to a special conductive adhesive tape used in electron microscopy.

Figure 2 shows the braking test bench on which the engine tests were carried out. Figure 3 shows the STPiW-3 test bench for testing common-rail fuel injection pumps and injectors, and a stereoscopic microscope that was used in the study. Temperature measurements were taken using a FLIR thermal imaging camera.


(a) (b)

Figure 2. Engine test rig: (a) Fiat 1.3 JTD engine with Automex electro-spinning brake, (b) computer station


(a) (b)

Figure 3. Measuring equipment used: a) STPiW-3 fuel injection pump and injector test bench, b) stereo microscope

During the fuel injectors test, the injection and overflow doses and the nozzle opening pressure were measured. Four injection doses were measured during the tests: 1 – full load, 2 – emission, 3 – idle and 4 – pilot. The test parameters are as follows:

- For dose 1: system pressure 135 MPa, injection time 780 µs;
- For dose 2: system pressure 80 MPa, injection time 700 µs;
- For dose 3: system pressure 30 MPa, injection time 420 µs;
- For dose 4: system pressure 80 MPa, injection time 260 µs.

The leakage test was performed at 145 MPa, and the nozzle opening pressure was in the range 14–21 MPa. The leakage test consisted of setting the fuel injector to maximum pressure and checking the overflow value and organoleptically for leaks at the threaded connections. If the actual parameters were within the set range, the fuel injector theoretically qualifies as functional. The overflow quantities were tested during the leakage and maximum load dose test. The unit of dose rate was 1 mg per fuel injector cycle, i.e., needle lift.

In addition, micro-dose tests were carried out on the STPiW-3 test bench. This test is performed for electromagnetic fuel injectors at an injection pressure of 30 MPa and an injection time of 300 µs. In order for this test to be effective, it was performed first immediately after removal from the engine, the injector was not previously washed in an ultrasonic cleaner or subjected to an injection pressure and time on the test table above the values mentioned.

3. RESULTS

3.1 Results of Engine Tests

The dynamometer tests analysed the performance of a compression-ignition engine with a common-rail system on operational and non-operational fuel injectors. During the tests, the engine's operating parameters of power (P), torque (T) and SFC were measured, as well as ecological emissions of nitrogen oxides and hydrocarbons, smoke opacity and dioxide content in the exhaust gas. The measurements were taken as external characteristics as a function of engine speed. The results of the torque and power measurements of the engine running on the tested fuel injectors are shown in Figure 4.

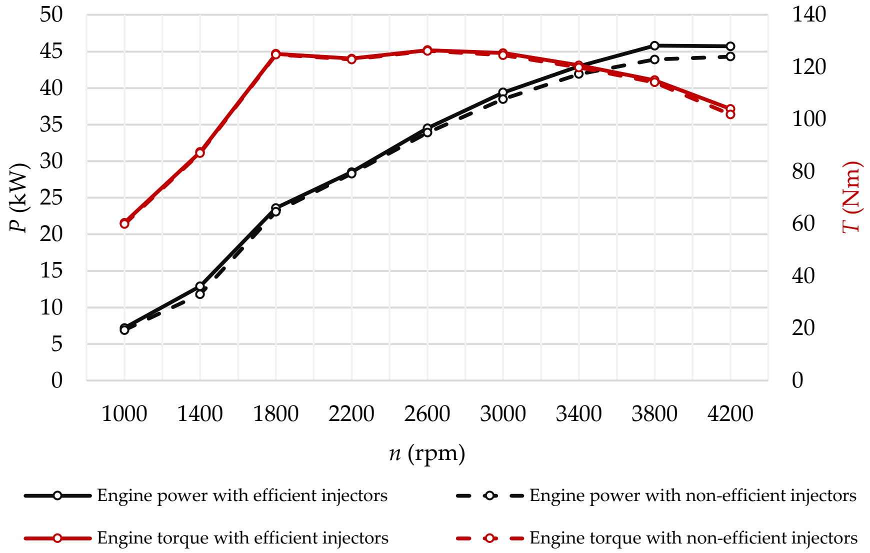

Figure 4. Power and torque characteristics of the engine running on efficient and non-efficient fuel injectors

SFC is an important indicator that determines the efficiency of an engine [27,28]. This parameter determines the amount of chemical energy that is needed to produce 1 kWh (Figure 5).

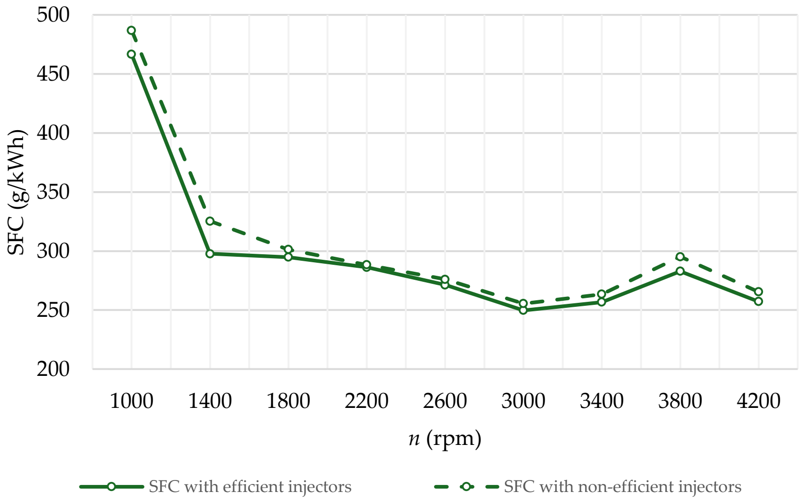

Figure 5. SFC curves for the engine running on efficient and non-efficient fuel injectors

The measurement of the engine's toxic emissions (Figures 6 and 7) is a very good diagnostic indicator that characterises the combustion process in the cylinder working space [29,30]. Nitrogen oxides (NO_X) and hydrocarbons (HC) are pollutants resulting from the combustion of a combustible mixture. Their content in the exhaust gas depends on the type of fuel, the composition of the combustion mixture and the temperature in the combustion chamber. Malfunctions in the combustion equipment alter the dosage, which affects the composition of the combustible mixture. Sources of formation of nitrogen oxides are compounds of particulate nitrogen in the air and fuel-bound nitrogen. Hydrocarbons are formed in low-temperature areas of the combustion chamber. One of the causes of hydrocarbon formation is improper fuel atomisation. Inadequate atomisation of the fuel by the injector results in localised air-deficit zones, which promote the formation of hydrocarbons.

Carbon dioxide (CO_2) contributes to the greenhouse effect. It is a natural product of the complete combustion of fuel. The carbon in the fuel is oxidised to carbon dioxide in the presence of oxygen. Carbon dioxide values that are too low can be a sign that the injection system is not working properly. Soot is unburned carbon. Its particles are formed in cool areas of the combustion chamber where the oxidation process is incomplete. The main causes of soot formation are deteriorated fuel atomisation, excessive injection rates or leaks in the injection system, e.g., nozzle leakage [31].

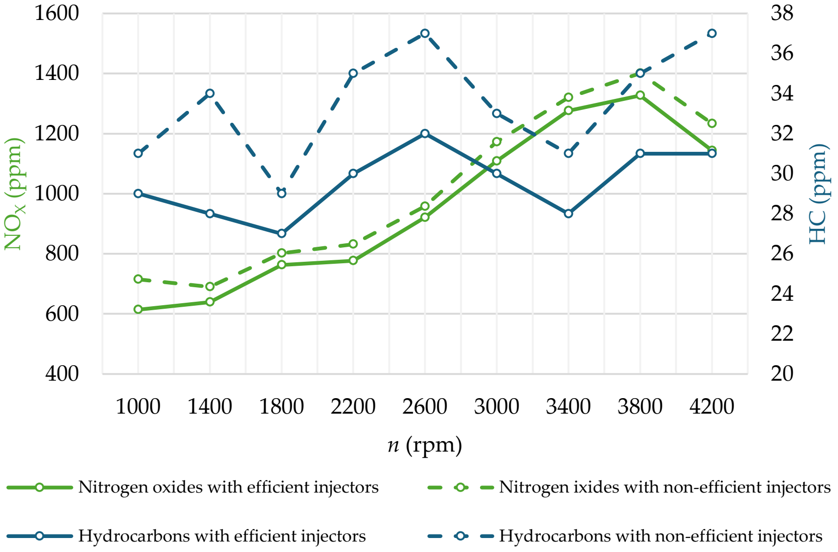

Figure 6. Emission characteristics of nitrogen oxides and hydrocarbons for the engine operating with efficient and non-efficient fuel injectors

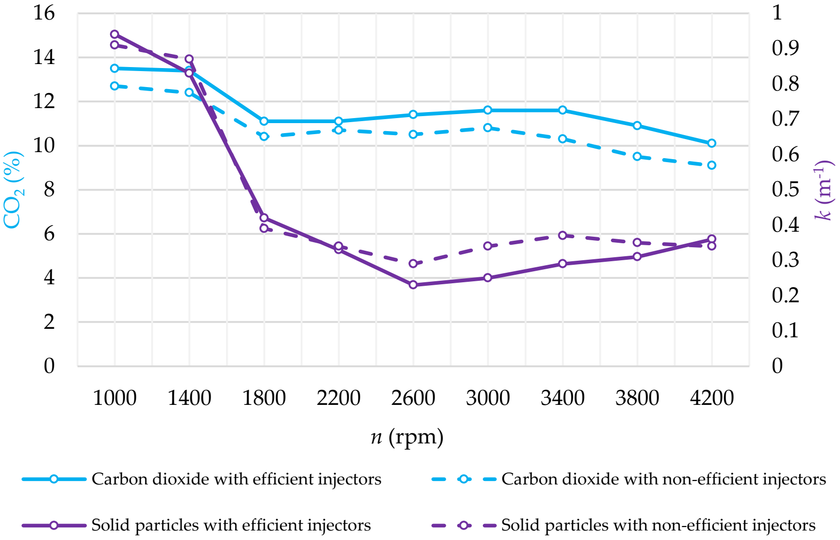

Figure 7. Solid particles and carbon dioxide characteristics of the exhaust gas for the engine running on efficient and non-efficient fuel injectors

3.2 Results of Laboratory Tests

Tables 2–5 show the results of measurements of the operating parameters of the fuel injectors tested.

Table 2. Results of measurements of operating parameters of injector no. 1

Test	Set Parameters	Actual Parameters
Leakage	0–70 mg	55.00 mg
Dose 1	D[1]: 28.12–40.67 mg	29.08 mg
	R[2]: 5–68 mg	72.00 mg
Dose 2	15.04–22.56 mg	14.05 mg
Dose 3	0.24–3.12 mg	0.34 mg
Dose 4	0.24–3.28 mg	0.55 mg
Opening the atomiser	14–21 MPa	23 MPa

[1] Injection dose, [2] Return

Table 3. Results of measurements of operating parameters of injector no. 2

Test	Set Parameters	Actual Parameters
Leakage	0–70 mg	49.00 mg
Dose 1	D[1]: 28.12–40.67 mg	31.03 mg
	R[2]: 5–68 mg	65.00 mg
Dose 2	15.04–22.56 mg	16.24 mg
Dose 3	0.24–3.12 mg	0.67 mg
Dose 4	0.24–3.28 mg	1.12 mg
Opening the atomiser	14–21 MPa	18 MPa

[1] Injection dose, [2] Return

Table 4. Results of measurements of operating parameters of injector no. 3

Test	Set Parameters	Actual Parameters
Leakage	0–70 mg	73.00 mg
Dose 1	D[1]: 28.12–40.67 mg	25.85 mg
	R[2]: 5–68 mg	84.00 mg
Dose 2	15.04–22.56 mg	12.74 mg
Dose 3	0.24–3.12 mg	0.12 mg
Dose 4	0.24–3.28 mg	0.31 mg
Opening the atomiser	14–21 MPa	20 MPa

[1] Injection dose, [2] Return

Table 5. Results of measurements of operating parameters of injector No. 4

Test	Set Parameters	Actual Parameters
Leakage	0–70 mg	59.00 mg
Dose 1	D[1]: 28.12–40.67 mg	30.04 mg
	R[2]: 5–68 mg	69.00 mg
Dose 2	15.04–22.56 mg	15.01 mg
Dose 3	0.24–3.12 mg	0.31 mg
Dose 4	0.24–3.28 mg	0.72 mg
Opening the atomiser	14–21 MPa	27 MPa

[1] Injection dose, [2] Return

During micro-dose tests on the STPiW-3 test bench, all injectors tested had dose values of 0 mg. While testing on the STPiW-3 test bench, a temperature distribution analysis was also carried out for efficient and non-efficient fuel injectors. An example image taken with a thermal imaging camera is shown in Figure 8.

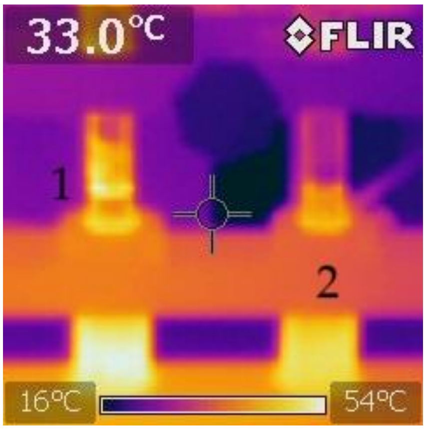

Figure 8. Temperature measurement on the body of the tested fuel injectors: 1 – non-efficient fuel injector, 2 – efficient fuel injector

The results of the temperature measurements on the body of the fuel injectors tested are shown in Table 6. The temperature of an efficient fuel injector in the nozzle area should be 50–60°C, and the valve area 45–60°C. Temperature measurements were taken at the maximum load dose (Dose 1).

Table 6. Temperature measurement results in the nozzle and valve areas of the tested fuel injectors

Injector No.	Nozzle Area (°C)	Valve Area (°C)
1	83	73
2	78	71
3	87	69
4	81	75

Figures 9 and 10 show fuel injector contamination samples taken from the precision pair elements shown in Figure 1, labelled 1, 2 and 3.

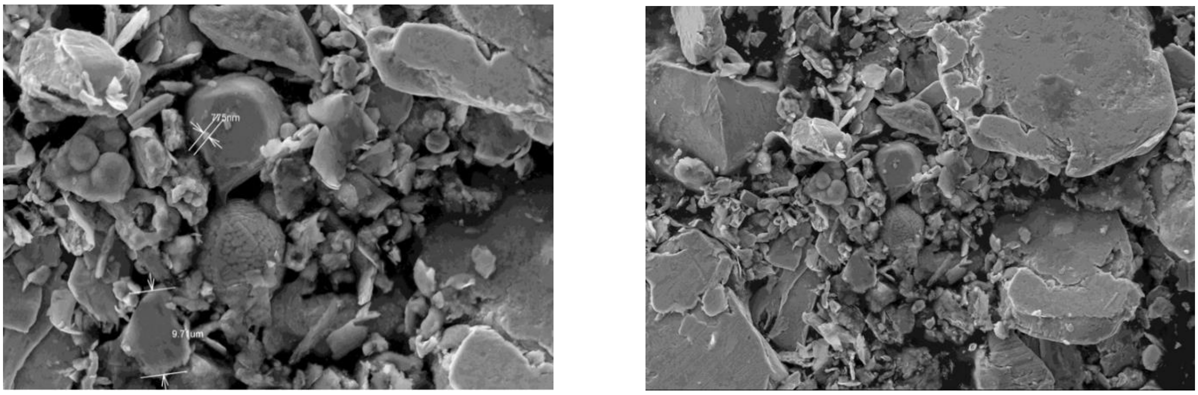

Figure 9. Contaminants taken from the nozzle area

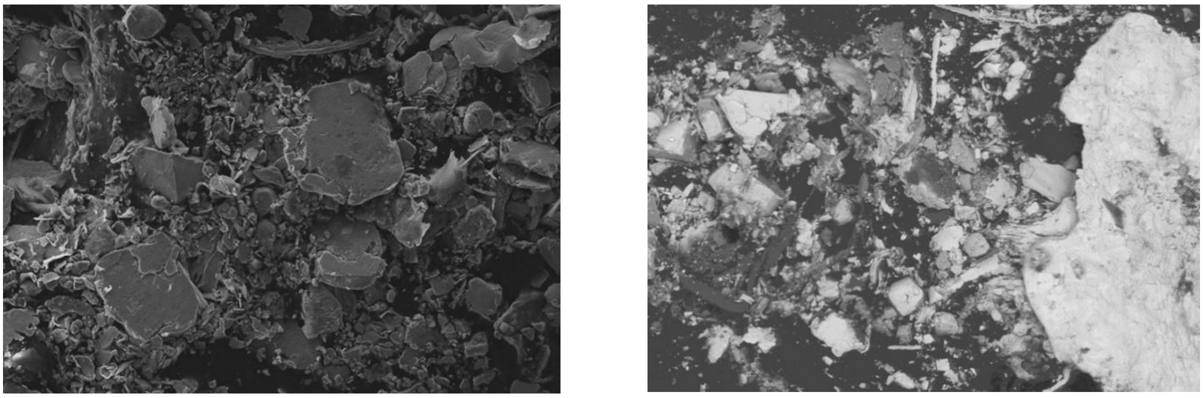

Figure 10. Contaminants taken from the valve area

Microscopic analysis showed mainly iron, carbon, oxygen and nickel in the precision pair elements and negligible amounts of silicon and aluminium. Table 7 shows the percentage of pollutants in the study areas.

Table 7. Percentage of pollutants in the study areas

Area	C (%)	O (%)	At (%)	Si (%)	Fe (%)	Ni (%)
Nozzle	43.5	49.8	1.2	2.5	2.9	0
Valve	2.3	0	0	0.7	50.1	49.6

4. DISCUSSION

Analysing the microscopic results, it can be concluded that the chemical composition of the debris taken from the fuel injectors indicates that some of it entered the system with fuel from outside, and the metallic part originated in the high-pressure pump. The metallic filings coming from the high-pressure pump are mainly deposited on the elements of the precision pairs of the valve piston and the valve itself in the area of the bore-ball association. On the other hand, elements such as silicon and sodium, which originate externally, were found on the elements of the nozzle precision pairs. Their location affects the size of the overflow dose, as the precision pairs seal the valve and the atomiser. The overflow rate is the discharge of the fuel injector during operation. Although the set parameters on the test bench show its maximum values at 60 mg, it is accepted in practice that a fuel injector that reaches an overflow dose of more than 40 mg should be disassembled, cleaned and tested. The fuel injector needle rises to a height of 50–60 µm during operation. Contamination on the precision vapour elements causes the working range to decrease and the fuel injection delay to increase. Fuel injection delay is the time from when the injector coil is actuated to when fuel delivery starts. In electromagnetic fuel injectors, this period varies between 400 and 500 µs. In used fuel injectors, this period is even more than 700 µs. This time shift affects the organisation of the combustion process of the combustible mixture in the engine compartment. It alters the advance time of the fuel injection, resulting in a delay of thermal reactions in the cylinder working space. This affects the performance of the engine mainly ecologically. Engine tests showed that an engine running on non-efficient fuel injectors had increased nitrogen oxide and hydrocarbon emissions over the entire speed range. This was caused by a change in the fuel injection advance angle and the disappearance of the pilot dose, as shown by the micro-dose test.

Nitrogen oxides and unburned hydrocarbons are formed in the combustion chamber in the area of high temperatures caused by excess oxygen. When the pilot dose disappears, the auto-ignition delay period is extended, and there is a sudden increase in cylinder pressure in the next stage. This causes a rapid rise in temperature, which promotes the formation of nitrogen oxides and hydrocarbons. The toxic substances in the engine compartment form locally in different areas. Soot is formed in areas with lower temperatures and nitrogen oxides in areas with higher temperatures. An examination of the injection rates on the test bench showed that all fuel injectors had under-injected. This means that the engine was running at excess air, which promotes the formation of nitrogen oxides. Carbon dioxide is formed by the oxidation of paraffinic hydrocarbons contained in the fuel or the further oxidation of carbon monoxide. Carbon monoxide is formed in the low-temperature areas of the combustion chamber. Analysing the laboratory results, the lower carbon dioxide emissions for the inoperative fuel injectors are due to the fact that the temperature was high enough during the combustion process that the carbon monoxide content itself was reduced. Engine operating parameters, such as power, torque and SFC, were at similar levels for the worn and efficient injectors. From the analysis of the tests, the final maximum cylinder pressure had a similar value.

The effect of fuel injector contamination on the emission of toxic substances in the exhaust gas was investigated by Badawy et al. [32]. They analysed the operation of a GDI petrol engine with deposits inside the nozzles. Optical analysis showed that the fuel spray changed under the influence of the contaminants. The study showed that the coked fuel injectors worsened the combustion process in the engine plenum. The nature of the fuel jet and dose influences the formation of soot and hydrocarbons in the exhaust gas. Kiplimo et al. [33] analysed how the fuel jet and exhaust gas recirculation (EGR) affect the formation of toxic substances such as nitrogen oxides, carbon monoxide and hydrocarbons. The study showed that carbon monoxide and hydrocarbon emissions are mainly influenced by parameters such as fuel jet atomisation and injection pressure, and nitrogen oxide emissions by EGR.

A distinction is made between qualitative and quantitative parameters of fuel injection into the engine combustion chamber. The qualitative ones include: atomisation, range, angle of spread, width and speed of the fuel jet. Quantitative ones, on the other hand, include the injection rate [34]. The formation of carbonaceous pollutants (soot, hydrocarbons or carbon monoxide) is mainly influenced by qualitative parameters, while the formation of nitrogen oxides is influenced by the injection rate and fuel injection characteristics. Fuel injection characteristics include parameters such as injection advance angle and the number of cycles delivered to the engine during the compression stroke. Typically, in common-rail systems, there are pilot, main and afterburning cycles. In the tested engine, there were two doses: pilot and main. During the tests, external engine characteristics were measured. The pilot dose occurred up to 1,700 rpm, and then at higher loads, the engine only ran on the main dose. This is because the injection advance angle decreases with increasing speed. Once a certain value is exceeded, there is no space to perform pilot doses.

The parameter describing the injector's ability to generate the number of doses during one engine cycle is the fuel injection delay through the injector. This is the time between the injector being triggered and the nozzle opening. In the injectors tested, it was 500 µs. This parameter oscillates within the norm, as its maximum value is over 600 µs for this type of fuel injector. All these parameters affect the combustion process in the combustion engine. Analysing the results of the tests carried out, it is apparent that the cause of the injectors' malfunctions is contamination in their key components (Figures 9 and 10). These affect the basic parameters of fuel injection. Slightly reduced injection volumes resulted in increased nitrogen oxide emissions in certain areas of engine operation (Tables 2 to 4). In addition, due to internal leakage, the injectors tested achieve a higher operating temperature (Figure 8). By analysing the power and torque characteristics of the engine running on the efficient and non-efficient fuel injectors, which are almost identical, it can be concluded that the maximum pressure in the combustion chamber did not change. If this were the case, the engine would have obtained a different power for the two types of fuel injectors. The formation of toxic substances in the cylinder headspace is influenced by areas of either deficiency or excess fuel, which is why the engine emits toxins in different proportions in different operating ranges.

5. CONCLUSIONS

Analysing the results of the experiment carried out, it can be concluded that the degree of fuel injector wear mainly affects the environmental performance of a modern compression-ignition engine with a common-rail system. The study showed that analysis of the exhaust gas composition can support the diagnostic processes of the fuel apparatus. The task of the fuel injector is to distribute and atomise the fuel in the cylinder working space. Its main operating parameter is the injection rate, which must be appropriate depending on the load. Microscopic analysis showed that in the injectors studied, foreign impurities are typical of glass and metallic filings come from the injection pump. These elements settle on the precision pairs affecting the operation of the entire unit. Typical symptoms of this type of wear are an inflated overflow rate and reduced injection. This condition affects the operation of the entire engine. The one way to improve engine performance is to replace the worn components and clean the entire system.

However, when analysing the results of the experiments carried out, it is apparent that the main cause of wear in the components of the injection equipment is impurities in the fuel. The origin of these contaminants is external and internal. External contaminants include anything that has entered the vehicle's fuel tank from the environment (sand, filings, paint from the tank, corrosive dirt). Internal contaminants, on the other hand, mainly include metallic filings from mating components. The sub-assembly of the high-pressure injection equipment of a common-rail system that generates metallic filings is the injection pump. These contaminants are transported with the fuel to the fuel injectors, causing wear. The quality of the fuel and the pump design are responsible for the production of metallic filings by the pump. Metallic filings are mainly formed on the pump raceways of the fuel injection pumps and, to a lesser extent, on the eccentric bearing of the pump drive shaft. In general, any high-pressure pump tends to produce metallic filings, but if these are larger than 10 μm, they do not usually escape. The metallic filings are usually crushed on the eccentric bearing of the high-pressure pump. This reduces their size so that they enter the high-pressure section of the pump and are pumped with the fuel throughout the system.

One way to reduce the production of metallic contaminants in the pump is to introduce a service procedure that involves cleaning the injection pumps during major vehicle maintenance. This is the only way to reduce the emission of these contaminants and extend the service life of the entire injection equipment. Each fuel filter has a water separator. This collects the water that is in the fuel. The procedure for draining the water from the filter is very simple and usually involves unscrewing a screw, dumping the contaminated liquid and turning it off. It is very rare for vehicle users to perform this procedure. Even in authorised service centres, during small inspections where the filter is not replaced, this operation is usually not performed. The tasks of fuel for internal combustion engines are to have compliant combustible and lubricating properties. A contaminated filter causes a reduction in fuel quality. If the water separator is filled, then water enters the entire system, degrading the lubricating properties of the fuel oil. This causes wear to the entire injection system (pump and especially the fuel injectors).

The fuel injectors tested had contamination from outside and metallic filings from the high-pressure pump. These filings originated in the drive section of the pump at the eccentric bearing - shaft interface. The cause of this amount of contamination was improper operation of the system by not cleaning it periodically and not having a periodic filter service procedure. The internal combustion engine is a device consisting of many sub-assemblies. One of these is the fuel supply equipment. Its deficiencies result in inadequate operation, which usually manifests itself in slightly increased emissions of toxins in the exhaust gas. It is therefore important that the maintenance procedures for each engine system are carried out correctly. This will increase its service life and have a positive impact on the environment.

FUNDING

This study was not supported by any grants from funding bodies in the public, private, or not-for-profit sectors.

CONFLICT OF INTEREST

The authors declare no conflicts of interest.

AUTHORS CONTRIBUTION

T. Osipowicz: Conceptualization; Methodology; Software; Validation; Formal analysis; Investigation; Resources; Data curation; Writing - original draft; Writing - review & editing;Visualisation; Supervision; Funding acquisition

R. Grzejda: Writing - original draft; Writing - review & editing; Visualisation; Project administration

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LIST OF ABBREVIATIONS

BEI	Backscattered Electron Image
CFD	Computational Fluid Dynamics
EDS	Energy Dispersive Spectrometry
EGR	Exhaust gas recirculation
SEI	Secondary Electron Image
SFC	Specific fuel consumption

APPENDIX A. WEAR PROCESSES OF COMMON-RAIL SYSTEM COMPONENTS

The analysis of the wear process of the injection equipment components is intended to identify the critical tribological pairs of the high-pressure fuel supply system of the common-rail system. The high-pressure fuel supply system of the common-rail system consists of an injection pump, high-pressure lines, pressure accumulator, fuel injectors, temperature sensor and pressure regulators [35,36]. The operating conditions for this system are high temperatures and pressures of 20–200 MPa. This environment causes the components of the injection pump or fuel injectors to undergo wear processes. In a high-pressure common-rail system, the actuators are the fuel injectors, the pressure regulating system and the injection pump. The function of the injection pump is to build up (build up fuel) pressure in the system regardless of the operating conditions. The task of the pressure control system is to control the set pressure during engine operation regardless of the operating conditions. The system consists of a high-pressure regulator located on the high-pressure side of the injection pump or common-rail system or a discharger located in the injection pump upstream of the high-pressure sections. The difference between the means of control is that the delivery regulator directs enough fuel into the sections to create the set pressure in the system, while the high-pressure regulator dumps excess accumulated fuel through an overflow channel to maintain the set fuel pressure in the system. In earlier designs, the system was controlled only by the high-pressure regulator, but a low-pressure regulator was introduced because of energy losses. In newer designs, the system is controlled on both the high and low pressure sides. The fuel injector is a device whose task is to distribute and atomise fuel in the engine combustion chamber. The operating conditions under which it operates are very severe. It is mounted in the engine head and the fuel atomiser is located directly above the combustion chamber. It is exposed to high pressures, temperatures and gaseous forces. Analysing the structure and operation of the common-rail fuel supply system, it can be divided into the pressure-generating component and the components responsible for supplying fuel to the combustion chamber.

The high pressure is generated in the injection pump sections. This is practically where the high-pressure part of the system begins. The accumulated fuel travels through the fuel lines to the pressure accumulator and then to the fuel injectors. The condition of the precision vapour components in both the injection pump and the fuel injectors depends on the efficiency of the entire system. Measures of the wear of the injection pump are the efficiency and the expense figures. The technical condition of the high-pressure section precision pairs is responsible for these parameters. If the high-precision vapour sections are worn, the amount of leakage increases, which affects the pump's fuel delivery rate and efficiency. In addition, increased leakage of the precision pairs causes an increase in the temperature of the component, which accelerates their wear processes. Studies have shown [37] that the temperature difference between worn precision pair components and efficient ones is about 20–30°C and rises with increasing system pressure. The operating conditions of the common-rail system intensify the wear processes of its individual components [38]. The fastest wear during operation is on the precision pair components in the fuel injector and injection pump. The wear processes of the common-rail system's injection system components can be divided into tribological and non-tribological (Figure A1). Most often, the wear intensity phenomena of fuel supply system components overlap, which shortens the service life of the component.

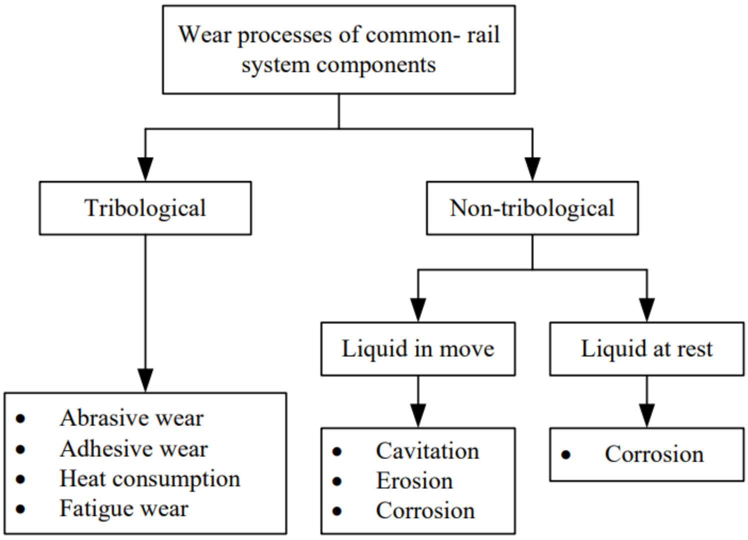

Figure A1. Wear processes of common-rail system components