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Hydrogen-Containing Fuel Influence on Compression-Ignition Engine Part Wear and Emissions of Toxic Substances

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Abstract: Issues related to the components of modern fuel equipment wear processes have been discussed. The fuel injector is one of the key elements of the fuel equipment system, because it is a device responsible for distributing and spraying hydrogen-containing fuel in the engine combustion chamber. It is mounted in the modern engine head directly in the combustion chamber. If the fuel injector is faulty, it affects the operating parameters and in particular the ecological parameters of the modern engine, such as the emission of toxic substances into the environment. Additionally, a hydrogen reactor has been installed in the Common Rail (CR) system, the task of which is to produce hydrogen. As a result of the temperature prevailing in the operating environment of the injection equipment, various types of wear occur inside the system, including hydrogen degradation. The types of degradation processes of precision pairs of modern fuel injectors have been analyzed and classified. Microscopic tests were performed to analyze the contamination in the fuel system and to compare the ecological parameters of the engine operating on efficient and worn fuel injectors. The emission of nitrogen oxides, carbon monoxide and soot has been analyzed as a key ecological parameter. It has been established that the loss of precision of pairs of elements of a damaged fuel injector significantly affects the size of the injection doses of the fuel mixture containing hydrogen.

Keywords: wear processes; emissions of toxic substances; steel; fuel injector damage

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1. Introduction

The most vulnerable elements of the CR high-pressure fuel supply system and their impact on the engine's emission of toxic substances into the atmosphere can be determined by the wear of injection equipment parts. The CR supply system consists of a fuel pump, pipelines, a pressure accumulator, fuel injectors, a temperature sensor and a pressure regulator and functions at high temperatures and pressures from 20 to 200 MPa. With the replacement of part of the initial fuel with hydrogen, the mode of operation of internal combustion engines (ICEs) and diesel engines (DDs) changes.

In particular, with an increase in its content, the pressure in the intake system increases, the index of compression polytropic decreases, the induction period lengthens, the intensity of combustion increases, which is manifested in the growth of the heat release rate and pressure, and there is a decrease in the duration of combustion, an extension of the afterburning period, and a drop in temperature exhaust gases, an increase in H_2O concentration in them, a linear decrease in CO_2 concentration, an exponential decrease in CO concentration, a linear increase in NO_x concentration in exhaust gases, and a change in excess air and engine efficiency. With the addition of hydrogen, the amount of exhaust gases and the concentration of HC practically do not change. When replacing part of the fuel with hydrogen in the DD, the pressure in the intake manifold and the composition of the hydrogen containing mixture, as well as possible hydrogen wear, should take into account elements of the hot tract. In practice, the ignition mode is adjusted, increasing the burning rate.

The effect of Brown's gas (HHO gas), which is added to the intake systems of Fiat Cinquecento, Renault Twingo and Opel Corsa, Skoda Octavia and Opel Combo engines, manifests itself already at idle speed. Concentrations of CO, HC and NO_x in the exhaust gases of cars are measured by the MAHA MGT5 analyzer (initially only in engines using standard fuel (SF) and then adding HHO gas) [1,2].

It was found that in the latter case, the concentration of the specified compounds in the exhaust gases of internal combustion engines decreases. In the intake system of the Fiat Cinquecento engine, idling, the combustion process deteriorates. Although the concentration of HC was lower by 24% and the amount of CO increased by 34% [1,2], the content of nitrogen oxides almost did not change. With the addition of HHO gas to the fuel, the concentration of unburned hydrocarbons decreases [1–6] and the NO_x content depends on the fueling method. In SI engines, with indirect gas injection during intake, the NO_x concentration decreased. In engines with a carburetor without feedback, it practically did not change, but increased in DD. Such operating conditions lead to intensive wear of the components of the fuel pump and injectors.

The purpose of the study is to assess the impact of the wear and tear of parts of the injection equipment on the emission of toxic substances in modern diesel engines.

Analyzing the literature, research on the use of hydrogen as a fuel additive is conducted in various directions. In CI engines, hydrogen can be used as a fuel additive in order to co-combust it with diesel oil. However, the optimal amounts in the combustible mixture are up to 10–15%. This is because the chemical properties of hydrogen are favorable for spark-ignition engines. Hydrogen itself has a zero cetane number, which disqualifies it as a clean fuel for vehicles with CI engines. However, as a fuel additive, it can support the combustion process and improve the ecological parameters of the engine, but as the same time it can affected by degradation and relaxation phenomenon of structural and functional engine materials [7–10]. The fuel equipment plays an important role in the process of preparing the combustible mixture. Its task is to supply fuel to the engine combustion chamber [11–15]. The critical elements of the injection equipment are the high-pressure pump and fuel injectors. In the high-pressure pump, as a result of its excessive wear, metallic filings are formed, which destroy the fuel injectors in the next stage [16].

In the CR system, the pump must stably supply fuel regardless of the engine speed and its operation is influenced by the design features of the high-pressure line. As the precision elements of the line pairs wear out, unauthorized leaks appear and the pump costs decrease, which is accompanied by an increase in temperature. The pump housing with a high-pressure regulator (or its flow rate) has a fuel temperature sensor and a high-pressure section shut-off valve, a high-pressure section drives shaft, a bearing and an eccentric. The tribological pairs are a cam on the shaft with an eccentric, an eccentric and a cup on the piston sections, a drive shaft and a bearing. The lubricant is diesel oil.

As a result of long-term operation, abrasive, fatigue and thermal wear of the components occurs, which contributes to corrosion. In high-pressure sections of the pump, the piston and the head are elements of tribo clutches. Due to the wear of precision parts, leaks increase, which leads to lower costs (especially at high pressures) and pump efficiency. In the CR system, the fuel injector affects the engine operation. Filings generated in the pump degrade the precision pairs and the valve seat in the fuel injectors. This affects the operation of the entire engine and its durability. As a result of the hydrogen degradation of the precision pairs, their operating parameters change, such as injection and overflow doses [17–25]. Hydrogen can be supplied to the engine combustion chamber in several ways: as an additive to fuel, where the carrier is a liquid, a hydrogen-generating device can be installed and added to the intake manifold and mixed with air, or an additional hydrogen injector can be added and the gas supplied directly to the combustion chamber or intake system. However, this solution requires additional installation of a hydrogen cylinder and the entire installation. It is possible to obtain hydrogen from fuel equipment by modifying its components [26–39]. Each of these methods is effective and the choice depends on the vehicle application.

The aim of this work is to assess the influence of wear of injection equipment parts on the emission of toxic substances in modern diesel engines operating on a combustible mixture enriched with hydrogen.

2. Investigated Materials and Testing Methods

Laboratory tests were carried out on an engine dynamometer (Figure 1). The research engine was a Fiat 1.3 JTD with a Common Rail system and an AMX eddy current brake. The exhaust gas content was measured using a MAHA smoke meter (MAHA Maschinenbau Haldenwang GmbH & Co. KG, Haldenwang, Germany) and a Capelec exhaust gas analyzer (Capelec Deutschland GmbH, Wolfertschwenden, Germany). Ecological characteristics were performed as a function of rotational speed at full engine load in accordance with the Polish Standard PN-EN ISO 8178-1 [12,40].

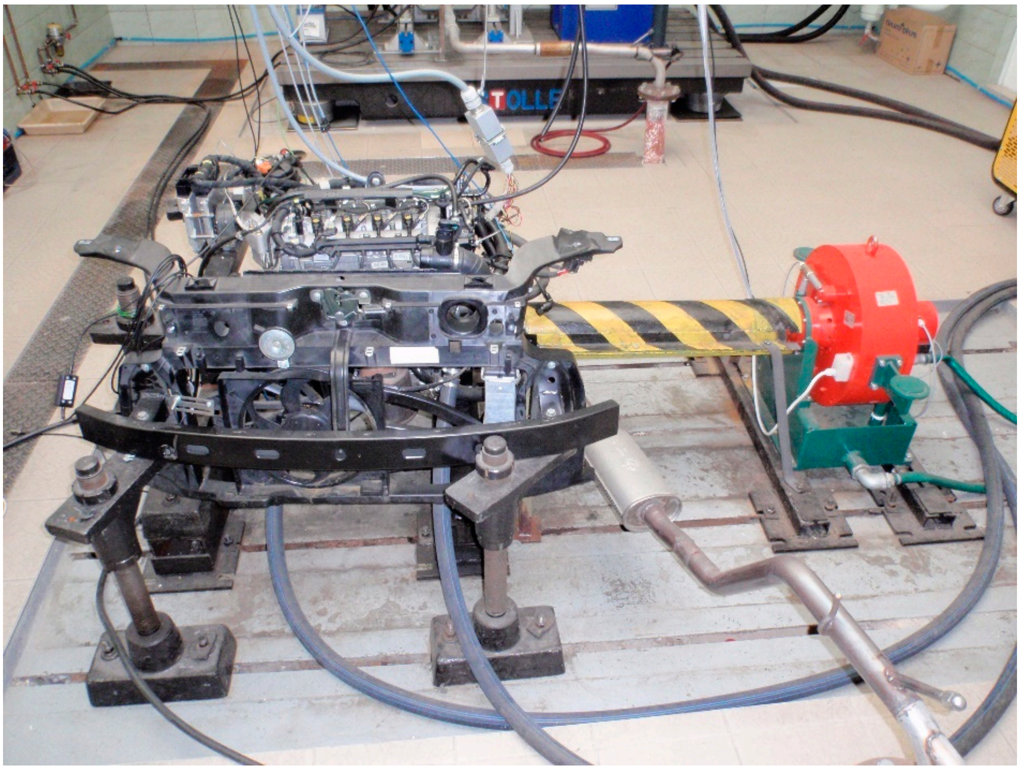


Figure 1. Test stand with a Fiat 1.3 JTD engine and AMX eddy current brake.

The pump housing with a high pressure regulator (or its flow rate) has a fuel temperature sensor and a valve that shuts off the high pressure section, the drive shaft of the high pressure section, a bearing and an eccentric. Tribological pairs are a cam on a shaft with an eccentric, an eccentric and a cup on piston sections, a drive shaft and a bearing. As a result of long-term operation, abrasive, fatigue and thermal wear of elements occurs [6–12], which contributes to corrosion. In the high-pressure sections of the pump, the piston and the head are the elements of tribo couplings.

Due to the wear of precision parts, leaks increase (especially at high pressures) and pump efficiency. In the CR system, the operation of the DD is affected by the fuel injector, made of heat-resistant steel type 55NiCrMoV7 (mass%: 0.55 C; 0.75 Mn; 0.25 Si; 1.0 Cr; 1.5 Ni; 0.45 Mo; 0.1 V; P, S—max 0.03) with anti-friction coating MoS_2. The pressure at the exit from the system, the time of opening the nozzle, the dose and the delay time of fuel injections (injection) were recorded.

Damaged surfaces and destruction of structural elements were examined with the help of electronic scanning microscopes Hitachi SU-70, ISM-6100, Shirley, NY, USA). The volume concentration of hydrogen in wear products (WPs) was estimated using a LECO TCH 600 (St. Joseph, MI, USA) by the method of infrared adsorption with sample melting.

The experiment was performed on an Automex AMX 200 engine dynamometer (KLAM AMERICA CORP@DENVER, Brighton, CO, USA). The research engine was a Fiat 1.3 JTD. During the research, its ecological parameters were measured as a function of rotational speed. The tested fuel injector is an electromagnetic Bosch generation 1.0. The atomizer has six holes.

Hydrogen for the fuel was introduced using a hydrogen reactor integrated into the fuel supply system. The primary function of the hydrogen reactor in the proposed setup is to enhance the combustion process of the air-fuel mixture in a modern CI engine. Examining the design of the Common Rail system, an additional catalytic reactor can be incorporated into the high-pressure accumulator, as shown in Figure 2. Inside the rail, a rod-shaped reactor with annular channels coated with a platinum catalyst was installed. These channels serve to expand the contact area for the catalyst and initiate turbulence in the fuel flow. Research indicates that the reactor's efficiency can reach up to 10%, depending on the system's temperature. The catalyst operates more effectively at elevated temperatures, with the rail temperature ranging between 50 and 70 °C [41].

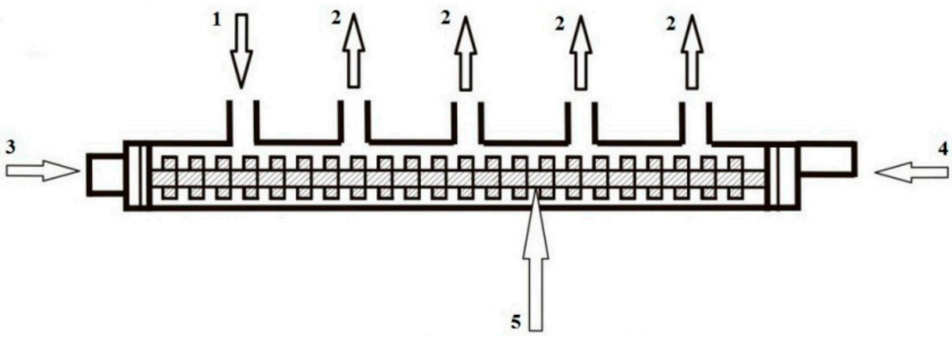


Figure 2. Modified high-pressure accumulator with a hydrogen reactor: 1—fuel supply, 2—fuel outlet to the system, 3—pressure sensor, 4—high-pressure regulator, and 5—hydrogen reactor.

3. Results of Experiments and Discussion

The results of the engine tests are presented in Figure 3. During the tests, the emissions of carbon monoxide, nitrogen oxides and soot into the atmosphere were measured.

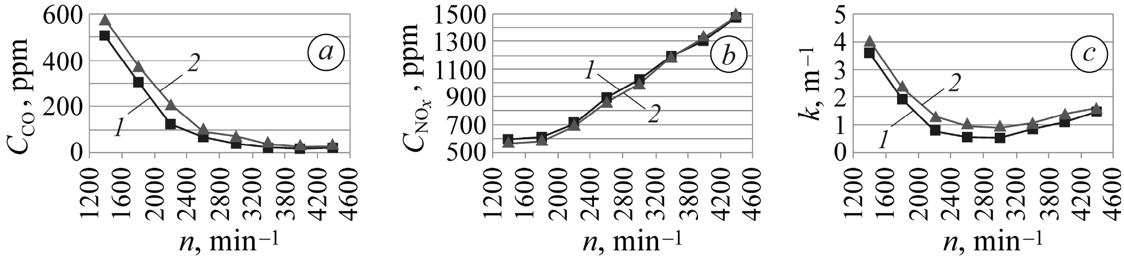


Figure 3. Dependence intensity of the emissions of carbon oxides CO (**a**) and nitrogen NO_x (**b**) and their smokiness (**c**) of exhaust gases, determined by the absorption coefficient of infrared radiation k on engine revolutions, where cases of healthy (2) and damaged (1) fuel injectors.

Destructive processes in injection equipment were analyzed in static and dynamic modes. The influence of kinematic and dynamic factors, as well as external influences on elements of precision pairs and other components of the system were not taken into account and for dynamic–kinematic-dynamic interaction and the influence of external factors on the structure of structural materials and the work of elements were evaluated precision pairs, as well as the relationship of all components of the fuel supply system.

It is advisable to study the wear processes of injection system components during downtimes and during operation. During operation, abrasive wear, cavitation [6], erosion, fatigue and adhesion and liquid friction occur, where diesel fuel performs the function of lubrication. In such systems, hydrodynamic lubrication is regulated, taking into account the physical properties and quality of such fuel. The force of liquid friction here is determined by the dependence:

$$T_{\text{liq}} = \eta \frac{V \cdot A}{h}, \quad (1)$$

where T_{liq} is fluid friction; η—dynamic viscosity; V is the relative speed of friction elements; A is the area of the contact surface; and h is the thickness of the lubricant layer.

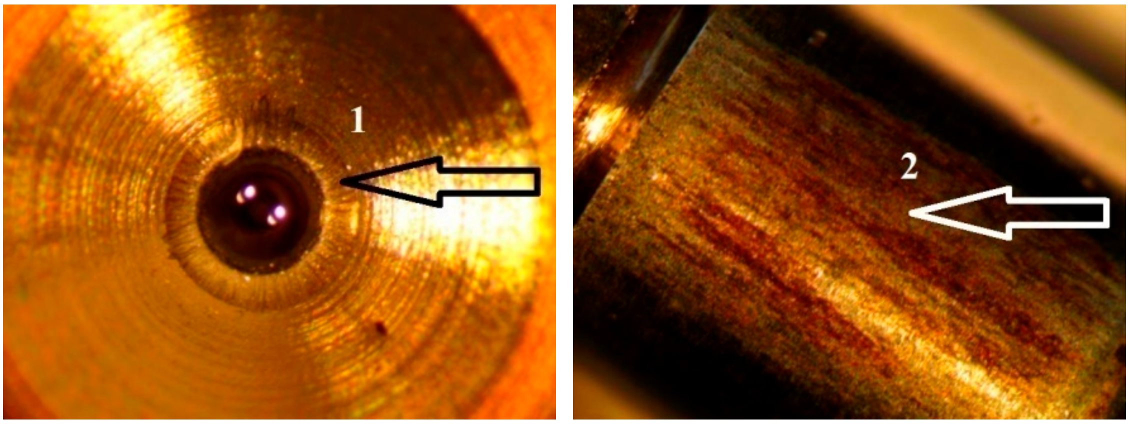
According to this dependence, the important role of the coefficient of dynamic viscosity of the liquid was established, which depends on the physical properties of diesel fuel and decreases with an increase in the temperature of the environment.

On the other hand, the wear of precision pairs affects the loss of mass and the structure of the surface layers of the friction elements. The degree of wear of the components of the injection pump and fuel injectors was assessed based on the results of micro-X-ray spectral analysis of the surface of the elements of precision pairs.

It was found (Figure 3) that the emissions of soot and carbon monoxide by the Common Rail Fiat 1.3 JTD engine (with a damaged injector) increased, especially noticeably during operation in the range of revolutions of 72,000–168,000 s^{-1} and the amount of emissions of nitrogen oxides NO_x did not change.

The formation of toxic substances in exhaust gases is influenced by the physical and chemical properties of the fuel and the parameters of the injected fuel stream. Hydrogen as a fuel additive changes the chemical properties of the combustible mixture. Studies have shown that the use of a small amount of hydrogen additive to diesel oil reduces the emission of nitrogen oxides [12]. This is because hydrogen has almost zero cetane number and its ignition temperature is 585 °C. These parameters mean that in the initial phase of combustion, hydrogen as a small fuel additive lowers the temperature and pressure in the engine combustion chamber [12]. This reduces the emission of nitrogen oxides.

In the second stage of the research, a microscopic analysis of the components of the pairs of precision fuel injectors was performed (Figures 4–7). In the first stage of these studies, a stereoscopic microscope was used (Figures 4 and 6).



(**a**) (**b**)

Figure 4. Damaged (due to cavitation) seat of the fuel injector (**a**) and the precision pairs of the piston of the control valve (**b**) (traces of cavitation, abrasive wear (1) and corrosion (2) are shown by arrows).

The increased smokiness of emissions is caused by the wear of fuel injectors. In particular, with a faulty injector, the number of fuel injection doses increases in the range of nominal speed of rotation (LL) and maximum load (VL), which is associated with wear and leakage of the valve seat.

Elements of precision steam on the valve closing and opening the injector gradually wear out as a result of operation and fuel continuously enters the combustion chamber (especially at high pressures). In addition, due to the leakiness of the seat, the fuel injector works without stopping due to the difference in pressure between the nozzle and the valve. Near the valve, the pressure is reduced, so the pin rises and fuel leaks into the combustion chamber are accelerated [10–12,14–20].

Traces and wear products of the elements of the damaged injector socket as a result of cavitation were evaluated (Figure 4a) by targeted statistical microstructural (Figure 5a), fractographic and elemental analyses (Figure 5b,c).

In fuel injectors, cavitation occurs mainly in the transition of the fuel injector socket (Figure 4a) (indicated by an arrow). At the same time, examining the precision pairs of the piston of the main valve (Figure 4b), traces of abrasive wear and corrosion were found, which leads to an increase in doses of injected fuel and an increase in the temperature of the injector.

Hydrogen was supplied to the fuel via a reactor mounted in a high-pressure accumulator. The idea of the reactor is as follows. The combustion process and heat release play a fundamental role during the operation of a compression-ignition engine. The main characteristics of this phenomenon are the time and speed of pressure and temperature increase in the engine chamber. The period of self-ignition delay plays an important role in shaping the phenomena related to the combustion of flammable mixtures in diesel engines. This is the time between the start of fuel injection into the engine combustion chamber and the appearance of the first foci of self-ignition. In the theory of combustion, the aim is to shorten this time as much as possible. The self-ignition delay (τ_i) of the flammable mixture can be calculated from experimental data according to the relationship (1).

$$\tau_i = const + \frac{T^m}{p^n} e^{\frac{E_a}{RT}} \tag{2}$$

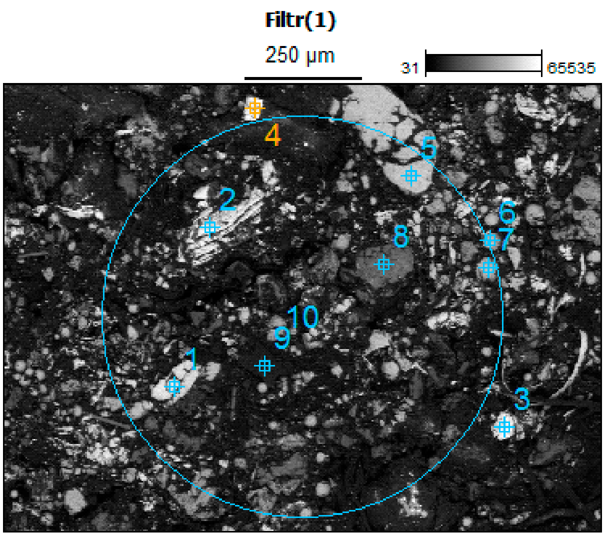
The equation indicates that the self-ignition delay period is influenced by the temperature and pressure within the engine's combustion chamber, as well as by the activation energy *Ea*. Activation energy is a fundamental parameter that determines the progression of a chemical reaction. Lowering its value increases the reaction rate constant, thereby accelerating the reaction. The physical interpretation of activation energy is as follows: during the reaction, interacting particles collide with one another. If every collision resulted in an immediate reaction, the process would occur instantly. However, in reality, all reactions take place at a finite speed, meaning that only a certain fraction of collisions lead to a reaction. Only those collisions where the particle energy at the moment of impact exceeds the average energy defined for a given temperature are considered effective. Activation energy represents the additional energy that particles must possess at the time of collision for the reaction to take place. Hydrocarbon fuels are multi-atom systems, meaning that activation energy can be described as the minimum kinetic energy required to exceed the system's potential energy for a chemical reaction to take place. In other words, it represents an energy threshold that reactants must surpass to transition into products. Lowering this energy reduces the self-ignition delay period, thereby enhancing the combustion process within the engine chamber. Compression ignition (CI) engine fuels are primarily composed of paraffinic hydrocarbons, represented by the general formula C_nH_{2n+2}. In these compounds, the energy required to break C–H bonds is higher than that needed to break C–C bonds. As the number of carbon atoms increases, less activation energy is required to break the molecular structure [12,41]. Increasing the energy available in the reaction environment, for example, by heating or introducing a catalyst that interacts with the reactant and forms an intermediate compound that rapidly converts into the final product, helps in overcoming the energy barrier. The chemical properties of fuels used in CI engines can be modified by dehydrogenating the predominant group of paraffinic hydrocarbons in the presence of a catalyst, converting them into olefins (C_nH_{2n}) while releasing a hydrogen molecule. Hydrogen, due to its high diffusion coefficient, strong ignition capability, fast combustion rate and wide flammability range, contributes to shortening the self-ignition delay period under the conditions present in the combustion chamber. Additionally, the presence of hydrogen molecules in the injected fuel stream can enhance fuel evaporation and mixing with air due to hydrogen's high diffusion coefficient. The catalytic reactor installed in the Common Rail (CR) system is designed to trigger the fuel dehydrogenation reaction before it reaches the injectors and to generate turbulence in the fuel flow. A key characteristic of turbulent flow is the fluctuation of momentum and kinetic energy, along with the facilitation of heat transfer. If the local fuel temperature in the sprayer increases as a result of additional vortices and increased flow time, the physical parameters of the fuel will also change, which will affect the spraying process [12].

In the second stage of the research, an electron microscope was used to determine the chemical composition of pollutants (Figures 5 and 7).

It was established that emissions of soot and carbon monoxide increased with a faulty fuel injector under the influence of a hydrogen-containing environment [21–31], especially noticeably in the range of engine rotation frequencies of 72,000–168,000 s^{-1}.

This is evidenced by the significant (up to C_H = 6.2 ppm) hydrogen content in wear products, despite antifriction coatings based on MoS_2 and spinel [21,26]. The faulty fuel injector contained increased injection doses in the range of the nominal frequency of rotation LL and maximum load VL.

The reason for this is wear and leakage of the fuel injector and valve seat. If the precision fuel elements on the closing and opening valves of the atomizer are damaged, fuel continuously enters the combustion chamber, especially at higher pressure. In addition, due to seat leakage due to pressure differences between the nozzle and valve zones, the fuel injector is constantly operating.



(**a**)

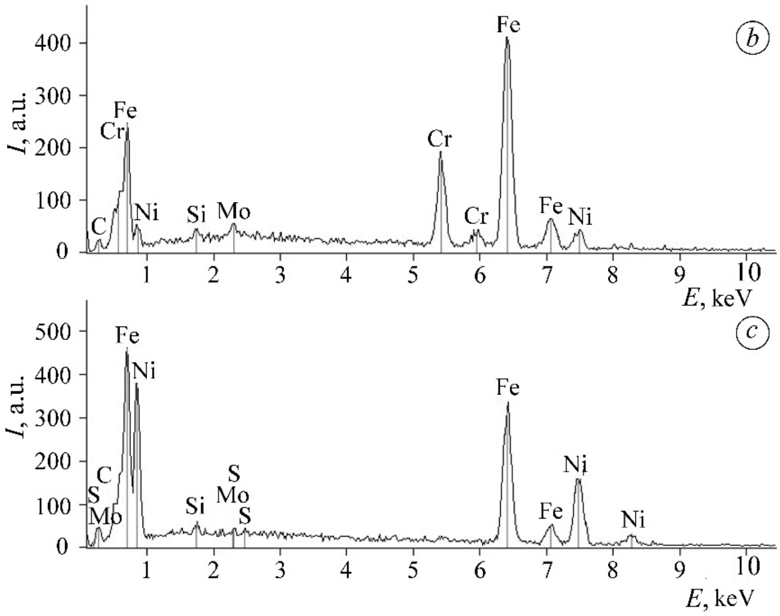


Figure 5. The microstructure of the wear products of the fuel injector socket as a result of the cavitation phenomenon (**a**) and local elemental analysis (**b**,**c**) (numbers—the points where the local elemental analysis was carried out (Table 1)).

Table 1. Results of EDX analysis of wear products on injector socket surfaces.

Area	C [%]	O [%]	Na [%]	Si [%]	Cl [%]	Cr [%]	Fe [%]	Ni [%]	Mo [%]
1	2.3			0.7			50.1	46.9	
2	2.4	3.3		0.8			37.3	56.1	
3	4.2						95.8		
4	1.8	1.7		0.3			96.2		
5	2.4			0.5		1.9	96.0		
6	2.0			1.1		1.0	94.7		
7	43.5	49.8	1.2	0.6	1.9		2.9		
8	40.2	51.7	1.8	1.3	1.0		1.3		
9	6.1	4.2		0.7			89.1		1.7
10	8.9	24.5		5.7			58.5		1.8

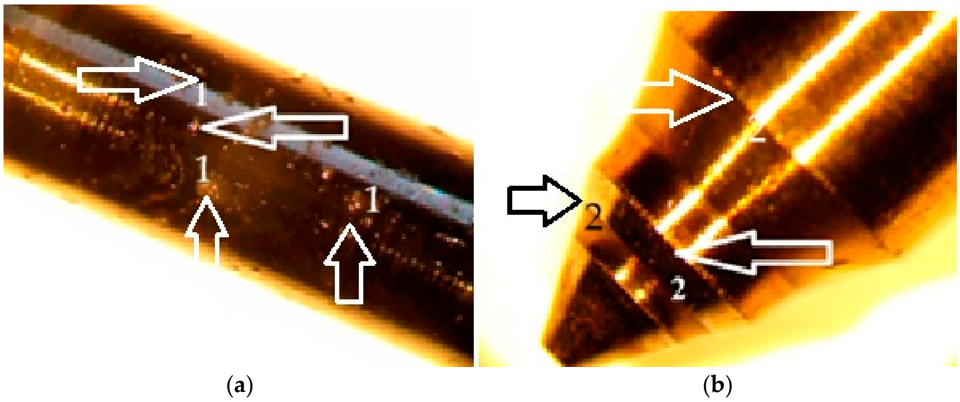


Figure 6. Damaged needle of the investigated fuel injector: (**a**) metallic filings (1), which degrade the precision pairs of the atomizer, (**b**) the needle damaged due to contamination, the places marked with arrows show the degraded precision pair of the atomizer needle (2).

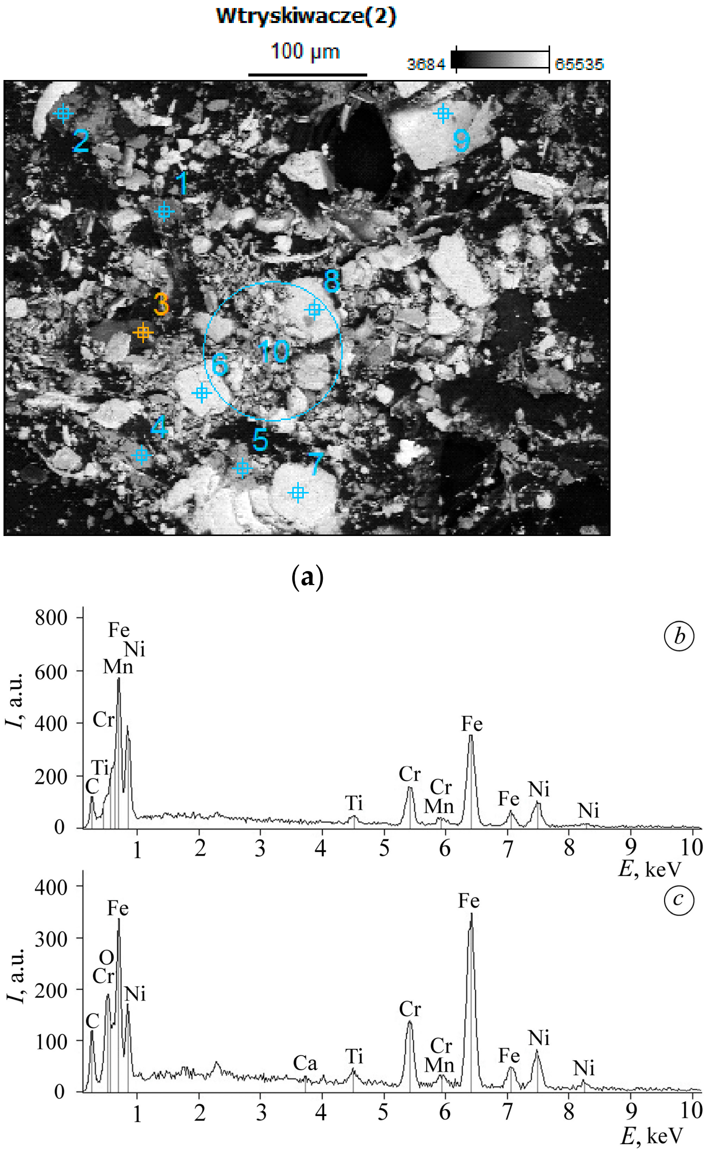


Figure 7. The microstructure of the wear products of the fuel injector socket as a result of the cavitation phenomenon (**a**) and analysis (**b**,**c**) (numbers—the points where the local elemental analysis was carried out (Table 2)).

Table 2. EDX results of metal shavings (wear products) of the fuel injector seat due to cavitation.

Area	C [%]	O [%]	Mg [%]	Al [%]	Si [%]	K [%]	Ca [%]	Ti [%]	Cr [%]	Mn [%]	Fe [%]	Ni [%]
1	11.8	6.0							1.6		80.5	
2	4.9							1.8	13.7	1.0	54.3	24.3
3	6.0	4.3					0.3	1.6	12.2	0.9	55.6	11.9
4	12.5										82.8	
5	3.5	29.2									65.8	
6	3.7	26.5							1.2		68.7	
7	2.9	31.1								1.4	64.7	
8	13.0	46.3	8.0	8.7	11.1	1.1					11.8	
9	52.5						1.6					
10	12.0	44.1	9.1	7.7	13.2	1.0						

Traces of wear of valve elements and nozzle seat (see Figure 4a) are the result of cavitation [6]. In addition, the precision element of the valve control spool shows signs of abrasive wear and corrosion, which increases the injection dose and the temperature of the nozzle.

On the needle of the fuel injector and the valve that closes it (Figure 6), metal shavings (with hydrogen content from 3.0 to 6.2 ppm) from the injection pump were found, which additionally accelerate wear.

The CR system always generates them during operation. Their formation is accelerated by hydrogen, which is present in the fuel. Metal chips and traces were also recorded on the needle element (Figure 6b), which opens and closes the fuel injector, also recorded metal shavings and traces of corrosion and cavitation, which cause nozzles to leak, especially at higher operating pressure in the system [32–39].

Hydrogen as a fuel additive affects its chemical properties to a small extent. The combustion process consists of several stages. The first and most important is ignition delay. The use of hydrogen as a fuel additive can shorten this period and improve the combustion process in the cylinder working space. In spite of that, diesel engines are economical thanks to their combustion process characteristics [41] and they have a high noise emission level and exhaust emissions of nitrogen oxide. And we confirm (Figure 3b) the issue from [41] that by continuously changing the value of compression ratio, it is possible to control the power and emissions. Presented in [41], the results of laboratory research on specific parameters (characteristics), such as compression ratio, fuel injection timing, engine speed, as well as load influence on combustion process and exhaust emissions, have confirmed our solution assumes the use of hydrogen in small amounts. This amount supports combustion processes in CI engines.

Hydrogen as a fuel additive affects its chemical properties. The combustion process consists of several stages. The first and most important is ignition delay. The use of hydrogen as a fuel additive can shorten this period and improve the combustion process in the cylinder working space and reduce nitrogen oxide emissions.

As it was established in [42], diesel engines have potential as power units for hybrid vehicles, but it is necessary to reduce the emissions of NO_x and smoke from diesel engines, due to their extremely negative impact on human health and the pollution of the environment with harmful exhaust gases, which is possibly due to introducing hydrogen admixing to alternative fuel. Due to this modern technology, there are possibilities to develop homogenous charge compression ignition, lowering engine displacement, catalytic treatment of raw combustion products, particle filters (which can be used as an effective source for the analyses of alloyed selective dissolution in the processes of wear and degradation of structural CI engines elements), partially at a maximum engine speed of 2325 rpm and a full load of 0.55 MPa [42].

At the maximum experimental engine speed and full load is the increased emission of smoke, which contributes to the reduction in NO_x emissions [42,43].

In Figure 6a,b the fuel injector needle is visible. Photos taken with a stereoscopic microscope showed metallic filings on the precision pair elements (1) and a damaged injector sealing valve on the needle (2). Microscopic analysis (Figure 7) showed iron content in the chemical composition of the impurities inside the tested fuel injector. These are internal impurities originating from the high-pressure pump. The filings degrade the precision pair elements of the fuel injectors and contribute to the formation of hydrogen corrosion.

Wear products consist of the elements of selective dissolutions in real working conditions that have appeared due to injector hydrogen degradation. A hydrogen-containing fuel sprayer with spiral-elliptical channels is the alternative injection strategy considered to mitigate wear effects.

4. Conclusions

1. It was established that the environmental parameters of the engine are affected by the degree of wear and tear of the hot high-pressure tract.
2. Fuel injector emissions increase under full load due to the wear of the precision valve and control piston pairs in a hydrogen-containing environment. As a result, the number of fuel injection doses increases and traces of cavitation damage were found on the surfaces of the valve seat.
3. Hydrogen combustion optimization involves the maximum reduction of the content of toxic substances in exhaust gases. Accelerated wear of injection equipment elements depends on hydrogen-containing fuel, which also lubricates kinematic elements.
4. If the socket is leaking, the fuel injector is constantly working and supplying fuel to the combustion chamber, especially at higher pressures and transient conditions. At the moment of increasing the load on the engine, the pressure and injection time of the fuel mixture increase, and therefore, its amount increases.
5. An excess of fuel occurs in damaged injectors, which worsens combustion in the engine chamber due to incomplete oxidation of the combustible mixture and a decrease in flame temperature. Therefore, soot and carbon monoxide emissions increase.

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