Increasing the Energy and Environmental Efficiency of Fuel Injectors in Diesel Engines

Dejan Janković[1,*], Žarko Mišković[2], Slobodan Radojević[2], Zoran Stamenić[2], Mileta Ristivojević[2] and Aleksandar Dimić[2]

[1] Tehnomotive ltd, Savska 27c, 11251 Ostružnica, Serbia
dejan.jankovic@tehnomotive.com
[2] University of Belgrade Faculty of Mechanical Engineering, Kraljice Marije 16, 11000 Belgrade, Serbia
{zmiskovic,sradojevic,zstamenic,mristivojevic,adimic}@mas.bg.ac.rs
[*]Corresponding author

Abstract: The fundamental components in railway, automotive and marine transportation vehicles, as well as in power generation units, are diesel engines. Fuel injectors are vital mechanical elements of diesel engines. They have a significant influence on the operational characteristics of diesel engines in terms of energy and environmental efficiency. Therefore, it is very important that fuel injectors perform their elementary function safely and reliably throughout their designed service life. The reliability level of fuel injectors depends on the working capability of their contact surfaces. Due to complex operating conditions – high surface pressures and temperatures, adhesion forces, and chemical and mechanical impurities in fuel – the contact surfaces are exposed to various types of surface damage: wear, erosion, cavitation, and fatigue. The service life of fuel injectors depends on the rate of development of surface degradation processes on contacting surfaces. The main question is how to slow down the development of this process. In this paper, a mathematical model has been developed to establish correlation between the most influential parameters affecting the contact surface degradation process: hardness, roughness, temperature, clearance, and fuel injector service life. Based on the developed model, the influence of individual parameters on the development process of contact surface degradation was analyzed. Verification of the developed model was performed based on the results of experimental testing of fuel injectors under real operating conditions, implemented according to an original methodology. It has been shown that contact surfaces hardness has the greatest influence on surface damage generation, followed by clearance, roughness, and to a somewhat lesser extent, fluid temperature.

Keywords: fuel injectors; diesel engines; DOE; wear; service life

1 Introduction

The first diesel fuel injection system with the common rail concept was patented in 1973. From then until today, many scientific works have been devoted to improving their energy and environmental efficiency, whether it is diesel engines in locomotives [1] [2] [3] [4] [5], automobiles [6] [7] [8] [9] [10] or heavy-duty vehicles [11] [12] [13] [14] [15] [16] [17].

The first passenger car equipped with a common rail fuel system was launched in 1997. This fuel system is currently being manufactured in a number of variations, including more than 1930 applications and producing over 40 million units. At present, the European Union Horizon 2020 research and innovation plan has been approved to study the effect of the injection pressure of 4500 bar and the supercritical phase transition in the alternative fuels and real fuels with rich additives [18].

The higher environmental standards for pollution reduction have led to a significant tightening of the operating conditions of diesel engines [19] [20] [21] [22] [23] [24] and the development of new types of engines [25] [26], which also deal with energy efficiency problems [27] [28]. Biodiesel continues to demonstrate significant potential as a viable alternative to conventional fossil diesel fuel in the global energy matrix. This renewable biofuel is predominantly produced from a diverse array of vegetable oils and animal fats, with palm oil constituting the largest feedstock share at 36% of global production. Soybean oil represents the second most utilized feedstock at 23%, followed by rapeseed oil at 14% [29].

The empirical data demonstrates continued potential for enhancing internal combustion engine performance parameters. Contemporary advanced IC engines have successfully achieved thermal efficiency metrics exceeding 40%, representing significant progress in thermodynamic optimization and energy loss reduction [30]. In the latest generation of diesel common rail internal combustion engines (IC engine) these requirements have led to an increase in fuel injection pressure in order to inject more fuel within a short injection interval and allow for multiple injections during a single cycle. To achieve complete combustion and reduce nitrogen oxides (NO_x) emissions while meeting the environmental standards, the most advanced diesel IC engines enable up to nine fuel injections within a single working stroke. This has improved engine performance, reduced engine noise, and enhanced exhaust gas regeneration via post-injection. All of the above advantages have increased the load on fuel injectors, specifically the contact surfaces of the actuators.

The application of coatings as a means of wear protection is already extensively used in the automotive industry, especially in fuel injection systems [31]. Research on a method to improve the efficiency of fuel injection system testing, particularly focusing on identifying faults during engine startup and acceleration phases has been studied in [32]. The study combines theoretical and practical analysis of hydraulic processes in Common Rail fuel systems, specifically examining diagnostics during idle and acceleration conditions. The main objectives were to reduce diagnostic time and enhance the accuracy of fault detection. Performance characteristics of a single-cylinder diesel engine under partial load conditions, focusing on fuel consumption, power output, and torque has been examined in [33]. When maintaining constant fuel quantity per cycle, the research found that torque and specific fuel consumption followed quadratic patterns, while power characteristics showed 3rd order polynomial relationships within the studied range.

Applying design of experiments – DOE reduces the number of experiments and allows multiple parametric analyses of factors affecting the assembly segments in which it operates. For the proper functioning of the fuel injectors it is necessary for their contact surfaces to maintain in tight tolerances, which is very difficult. During operating period of the contact surfaces, due to sliding wear and aggressive behavior of corrosion, very fast deviation from their allowable tolerance limits is present [31].

By measuring the return fuel temperature, the condition of the contact surface and the remaining operational lifespan of the fuel injector can be indirectly determined. The equipment for testing the condition of the critical parameters of contact surface determined by return flow temperature, tolerance gap and roughness is described in detail in this paper.

2 Pressures and Temperatures during Fuel Injection in Diesel Engines

During the fuel injection process in diesel IC engines, as investigated in this study, the pressure increases or decreases depending on the operating regime, which is directly related to the temperature. The injection process during the operating cycle, with the relationship between pressure, time, and the amount of injected fuel is shown in Figure 1. Based on the Figure 1, a clear correlation between pressure and the amount of injected fluid, can be seen.

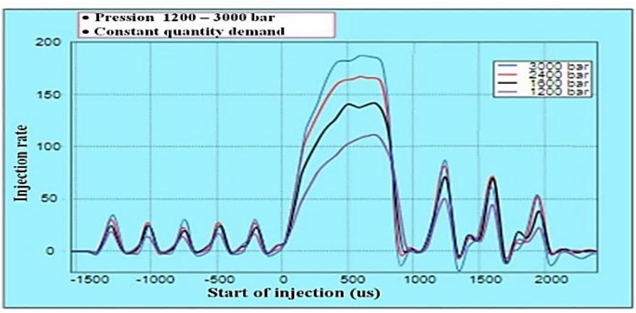

Figure 1

Injection during the Working Stroke [31]

From the provided information, it can be concluded that the fuel injector, specifically the contact surface of the actuator valve, is a potential wear occurrence site due to increased pressure and temperature. The choice of coating to protect the contact surface from wear on elevated pressure and temperature is crucial for the operational lifespan of the fuel injector.

The wear occurrence on the contact surface at a pressure of 3000 bar instantly generates an increase in the damage of contact surface of injector valve caused by increase of return fuel temperature, gaps tolerances and roughness. Mentioned parameters can be correlated with the condition of the contact surface and, thus, preventively stop the engine to protect it. It can also be used as a parameter for assessing the condition of the fuel injector. Temperature measurement is conducted in a low-pressure circuit, typically on the fuel filter housing via a sensor with an operating range from –30°C to +85°C. Its primary function is to maintain optimal temperature and protect the system from high temperatures in the low-pressure circuit. The temperature of the fuel injector return line at high pressure in an IC diesel engine of Euro 6d standard is correlated with the degree of damage to the contact surface. Therefore, this data is crucial for assessing the wear of the contact surface of the fuel injector (valve actuator), which has been confirmed under experimental conditions.

3 Impact of Temperature, Gap Tolerances and Roughness and Corrosion on Fuel Injectors during Operation

Destructive effects of corrosion on Diesel fuel injectors, within Common rail system focusing on performance and reliability impacts has been examined in [34]. The study reveals that corrosion significantly increases system failures through component wear acceleration and contaminant generation that disrupts normal injector operation. Both control valve/armature assemblies and nozzles exhibit comparable corrosion damage when exposed to high-pressure fuel environments. While electrical component failures occur less frequently, they prove catastrophic as these components cannot be cleaned or replaced, rendering the entire injector unusable.

Corrosion damage intensifies with extended operational time, affecting an increasing number of components and producing progressively severe wear patterns. Despite engineering advancements in design and materials in newer injector generations, the trend toward higher injection pressures continues to accelerate corrosive wear mechanisms. Component replacement availability emerges as a critical factor in injector repair effectiveness, as limited parts availability often prevents replacement of corroded components when necessary.

Injectors recovered from high-mileage engines frequently prove irreparable due to extensive deterioration that prevents restoration to original specifications.

Modern fuel injection systems operate with tolerances below 50 micrometers in the injector's moving parts [34]. Consequently, fuel particles of similar or larger size can cause blockages and sticking problems with the injector needle. Current filtering elements in these systems often prove inadequate at capturing all contamination or wear particles that are sometimes present in the fuel, leading to system failures. The conclusion presents this analysis technique as an effective diagnostic tool for detecting problems in diesel engine fuel injection systems. While continuous monitoring of fuel particles is necessary, installing a filter after the high-pressure pump isn't feasible due to the extreme pressures involved. Instead, they propose installing analysis devices at the fuel return outlet. This would allow detection of increased particle counts in the fuel, which could indicate either abnormal wear or external contaminants entering the system.

The temperature in the fuel injector of an IC diesel engine fluctuates during operation in dependence of operating regime on the requested pressure.

Besides the requirement to maintain high pressure, which increases the temperature, there is a sudden temperature spike in the range of 600-700°C during regeneration, i.e., burning accumulated combustion products in the Diesel Particulate Filter (DPF). High temperatures create maximum stress on the injector actuator valve's contact surface, causing typical wear patterns as shown in Figure 2.

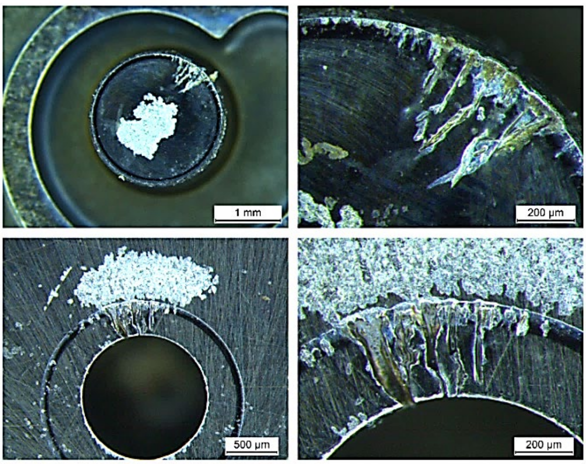

Figure 2
Worn-Out Injector Actuator Valve

The durability of the coating on the contact surface of the injector actuator valve is crucial in terms of its operational lifespan. The application of coatings in the automotive industry is essential because, due to environmental, economic, and energy demands, base materials, even after thermal and chemical enhancement, do not meet the required characteristics.

3.1 The Effect of Temperature on Physical Vapor Deposition (PVD) and Diamond-Like Carbon (DLC) Coatings

The choice of coating on the contact surfaces of fuel injectors is of utmost importance, and the tribological aspects of the coating at elevated temperatures have been analyzed in a large number of studies [35] [36].

The best representative of PVD coatings is the TiAlSiN coating, which has good oxidation resistance and mechanical properties at high temperatures. That is extremely important for heavily loaded machine elements such as fuel injectors. The results show that the $SiO_2{\bullet}nH_2O$ transfer film acts as a lubricant, reducing the coefficient of friction at room temperature [35]. The lack of oxide formation at 400°C indicated increased wear. However, oxides consisting of Al_2O_3 and SiO_2 formed at 600°C. Although the coefficient of friction of the coatings measured at 600°C is higher than those measured at 400°C, the wear rates of all samples are lower than those measured at 400°C. With a further increase in temperature, the rutile phase of TiO_2 might be responsible for the lower coefficient of friction of all coatings compared to those measured at 600°C [35]. The thermal analysis of different coatings is shown in Figure 3.

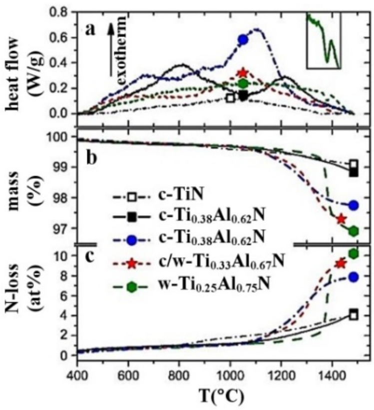

Figure 3

Comparative Presentation of Different Coatings [36].

Dynamic simultaneous thermal analysis combines (a) DSC and (b) TGA in an inert atmosphere (He) for the c-TiN, c-Ti0.48Al0.52N, c-Ti0.38Al0.62N, c/v-Ti0 .33Al0.67N and v-Ti0.25Al0.75N coating materials. The inset in (a) is a 4x magnified portion of the DSC signal for v-Ti0.25Al0.75N in the temperature range of 1300–1425°C. (c) Calculated N release due to the measured mass loss from (b) [36]. Unlike PVD coatings, DLC coatings and Si-DLC coatings of different compositions in the temperature range up to 500°C show that DLC coatings can be used at temperatures from 300°C to 400°C, while Si-DLC-based coatings remain stable up to 500°C. As a result of their good tribological properties and excellent temperature stability, new Si-DLC-based coatings have great potential for use in the automotive industry [37]. Figure 4 shows the relationship between hardness and the friction coefficient for DLC and Si-DLC coatings.

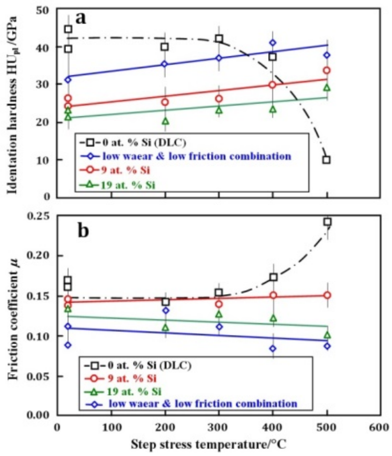

Figure 4
(a) Hardness (b) and Friction Coefficient of DLC and Si-DLC Coatings after Air Quenching [37]

3.2 Impact of Gap Tolerances on Contact Surfaces in Fuel Injector Performance

The clearance tolerance between contact surfaces of precision-engineered machine elements, such as injector actuators, requires tight specifications. Related contact surfaces significantly impact fuel delivery results. Uneven gap tolerances lead to decreased fuel delivery through the valve seat, resulting in poor spray quality and atomization during injection. Conversely, excessively large gap tolerances make valve seats and plungers crucial contact surfaces in fuel injectors, directly affecting fuel delivery quality. The highest fuel pressure occurs in the valve seat, with the highest wear velocity on the plunger. Large gaps can increase wear from the interaction of the cone and plunger, causing reduced pressure in the fuel system. Increased friction raises heat generation, lowering efficiency as oil viscosity increases over time. It's essential to monitor unwanted gap variations in vehicle fleets and their contact surfaces. A technically based valve system maintenance plan must be developed for optimal performance.

Maintenance frequency can be adjusted based on the influence of seals on gap tolerances. Caution is necessary if a worn valve seat is reintroduced below the proper gap size, especially due to the high corrosion rates of fuels. Proper mechanical and contacting parameters for injector components should be established. The operational profile should govern maintenance rules and limits. Simple mechanical rules affecting contact surface behavior allow for calculations of required wear on the plunger or coating to achieve the desired worn-out gap. Once the ideal worn-out gap is reached, testing is necessary to validate real condition and worn components. Experimental results demonstrate that limiting conditions determine critical contact surfaces and wear. The conical and cylindrical contact surfaces are critical, as they can create gaps between the volume spring and seating area. The injection parameters are optimized through precise measurements of clearances, which are set based on the seat face geometry until reaching maximum allowable pressure.

3.3 Effects of Surface Roughness on Fuel Injector Efficiency

The internal surfaces of fluid transporting components can become rough, impacting flow dynamics and processing technologies like nozzles and orifices. Rough surfaces reduce flow efficiency, choking characteristics, and work output variability. In fuel injectors, rough combustion chambers necessitate studying roughness effects on atomization and droplet formation linked to combustion.

The analysis of experimental findings [38] concerning diesel fuel injector nozzles has demonstrated a significant relationship between various performance indicators, including back flow, orifice discharge coefficient, and droplet sizes, and the surface finish of the nozzle. Generally, it has been observed that atomization quality improves, with a prevalent formation of larger droplets, in association with increased surface waviness or roughness. High-speed imaging of the droplets revealed negligible differences in mean diameters; however, the findings indicated a twofold increase in the number of oil droplets emitted from the nozzle with a rougher surface compared to its smoother counterpart. Additionally, variations in spray cone angles and penetration lengths were noted as a function of differing surface finishes. The results suggest that enhancements in fuel efficiency, as inferred from time-averaged lift curves, could be achieved through the utilization of precisely engineered machined surface configurations. Recommendations included reducing surface roughness to mitigate orifice cavitation, prevent surface pitting and decrease erosion rates.

4 Implementation of the Design of Experiment (DOE) using Taguchi Methods

The research [39] examines engine performance optimization and emission control using the Taguchi Design Methods as its analytical framework. The methodology incorporates Taguchi's orthogonal arrays, signal-to-noise (S/N) ratio analysis, and

ANOVA to determine optimal operating conditions and evaluate how different parameters affect both performance and emissions. Literature review reveals previous applications of the Taguchi Design Method [40] [41] [42] [43] [44], as well as other statistical analyses [45] [46] [47] in similar contexts. For instance, authors in [48] used an L9 orthogonal array to study how Exhaust Gas Recirculation (EGR) rate, fuel injection timing, and pressure influence NO_x emissions in diesel engines. These variables were examined in the context of a steam-injected diesel engine with EGR application.

Four principles of DOE were introduced by Ronald Fisher in 1926 [49]:

- The factorial principle
- Randomization
- Replication and
- Blocking

Analysis of above design principles relied primarily on manual calculation in the past. With the use of computers, DOE is becoming increasingly efficient, and in modern research, inevitable.

DOE is a systematic, efficient method that allows scientists and engineers to study the relationship between multiple input variables (factors) and key output variables (responses). It is a structured approach to data collection and discovery that is used for the following purposes:

- To determine whether a factor or set of factors has an effect on the response
- To model response behavior as a function of factors
- To optimize the response (JMP Statistical Discovery)

DOE is used to control the experiment for statistical purposes. The experiment plan is often used in the evaluation of various structures, physical objects and materials.

A decision matrix evaluates and prioritizes a list of options and is a decision-making tool. It first establishes a list of weighted criteria, and then evaluates each option according to those criteria. Table 1 tabulates the decision matrix obtained by applying DOE (JMP Statistical Discovery).

Table 1

Decision matrix obtained by applying DOE (JMP Statistical Discovery)

Factor assignment

		Main effects			**Interactions**			
		A	**B**	**C**	**D (A – B)**	**E (A – C)**	**F (B – C)**	**G (A – B – C)**
Tests	1	–	–	–	+	+	+	–
	2	+	–	–	–	–	+	+
	3	–	+	–	–	+	–	+
	4	+	+	–	+	–	–	–

5	–	–	+	+	–	–	+
6	+	–	+	–	+	–	–
7	–	+	+	–	–	+	–
8	+	+	+	+	+	+	+

5 Experimental Research

Temperature's impact on contact surface wear can be analyzed against specific threshold values. This analysis serves as an indicator for evaluating the condition of fuel injector contact surfaces.

Research in the field of threshold values for parameters of contact surfaces of machine elements with tight tolerances, in this case fuel injectors, was used as a starting point. By applying an experimental design and using three parameters - temperature, surface roughness and clearance between the valve injector contact surfaces (the critical parameter), on the pressure drop time, shown in Figure 5, can be determined.

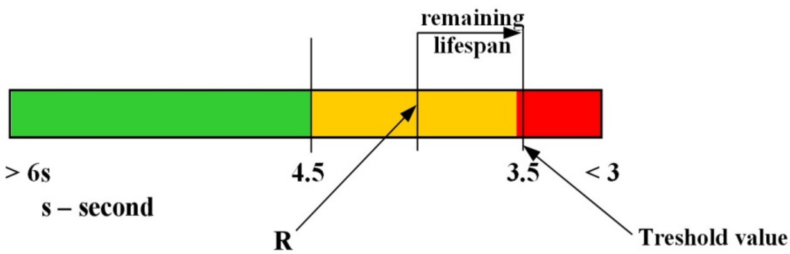

Figure 5
Pressure Drop Time

5.1 Mathematical Processing of the Experimental Results

Analysis of the elements of the mathematical model of the process, during repeated experiments n_0 times, the central point is performed after the operational implementation of the set orthogonal plan and obtaining of experimental results in several consecutive steps [50] [51].

5.2 Calculation of Model Parameters

The linear multiple regression coefficients are determined from an expression:

$$b_1 = \frac{1}{N}\sum_{u=1}^{N} x_{iu}\, y_u, \quad i = 0, 1, 2 \dots k \tag{1}$$

where:

x_{iu}- value of the x_i factor in the u-th experiment

y_u- value of objective function in the u-th experiment

N – number of experiments

Free member b_0 shall be determined from an expression:

$$\boldsymbol{b_0 = \frac{1}{N}\sum_{u=1}^{N} y_u} \tag{2}$$

Regression coefficients which define the interaction between the factors are determined from an expression:

$$\boldsymbol{b_{ij} = \frac{1}{N}\sum_{u=1}^{N} x_{iu}\, x_{ju} y_u, \quad i = 1, 2, \ldots, k;\ i < j} \tag{3}$$

It should be noted that the b_0 model parameters are determined on the basis of the results of all $N = 2^k + n_0$ plan points, and other parameters using only the results of $N = 2^k$ points allocated on the vertices of hypercube. Plan of experiments are given in Table 2, while Table 3 shows random parameters values (f_1 - clearance, f_2 - roughness, f_3 – temperature).

Table 2

A plan of the experiment

x0	**x1**	**x2**	**x3**	**R**	**Y=ln(R)**
1	–1	–1	–1	**6.2**	1.82455
1	1	–1	–1	**3.0**	1.09861
1	–1	1	–1	**6.0**	1.79176
1	1	1	–1	**2.4**	0.87547
1	1	–1	1	**2.6**	0.95551
1	–1	–1	1	**5.8**	1.75786
1	–1	1	1	**5.5**	1.70475
1	0	0	0	**3.7**	1.30833
1	1	1	1	**2.2**	0.78846
1	0	0	0	**3.7**	1.30833
1	0	0	0	**3.7**	1.30833
1	0	0	0	**3.6**	1.28093
				Sum	16.00290

Table 3

Random parameters values

Value	**min**	**average**	**max**
f_1 [μm]	2.0	2.8	4.0
f_2 [μm]	0.4	0.8	1.6
f_3 [C˚]	20.0	28.3	40.0

Three-factor function of pressure drop could be written in general form, according to the mathematical theory of the experiment:

$$\boldsymbol{R = C \cdot f_1^{p_1} \cdot f_2^{p_2} \cdot f_3^{p_3}} \tag{4}$$

where:

R – output of experimental tests

f_1, f_2, f_3 – input-influential factors

C, p_1, p_2, p_3 – parameters

Regression analysis involves the determination of numerical size of C, p_1, p_2, p_3 in the mathematical model R.

The general form of the regression dependence:

$$\boldsymbol{t = C \cdot Z^{p_1} \cdot H^{p_2} \cdot T^{p_3}} \tag{5}$$

where:

t – time of pressure drop (seconds)

C – constant

Z – clearance (micrometer)

H – roughness (micrometer)

T – temperature (degree Celsius)

p_1, p_2, p_3 – parameters

The result:

$$\boldsymbol{t = 20.08554 \cdot Z^{-1.21218} \cdot H^{-0.08586} \cdot T^{-0.13843}} \tag{6}$$

Assessment of significance is performed according to F_t – criteria which represents tabular value for given conditions of three-factor model i.e. the following condition must be satisfied:

$$\boldsymbol{F_{t<} F_0, F_1, F_2, F_3} \tag{7}$$

where:

F_t=10.13

F_r=1.954578

To obtain F_r = 1.954578, we use the center points from the experiment. This F_r value tells us about the precision of the experiment and the repeatability of measurements at the center point.

The results are: $\boldsymbol{F_0}$**=13672.78,** $\boldsymbol{F_1}$**=904.5926,** $\boldsymbol{F_2}$**=18.15274,** $\boldsymbol{F_3}$**=11.79**

5.1.1 Adequacy of the Experiment

By using Fisher criteria for assessing the adequacy of the model the ratio of parameters F_t, F_r is determined, in case which is the subject of this work:

$$\boldsymbol{F_r = 1.954578} \tag{8}$$

$$\boldsymbol{F_t = 10.13 > F_r} \tag{9}$$

Which according to expression:

$$\boldsymbol{F_{rLF} = \frac{s_{LF}^2}{s_E^2}} \tag{10}$$

indicates that $F_r < F_t$, where the multiple regression equation of the first order, as mathematical model, makes it appropriate and describes it by respective process.

6 Analysis of the Correlation of Temperature and the Critical Parameter (pressure drop time) on the Loss of Work Capacity and Energy Efficiency

The pressure drop time was determined by testing 120 injectors using an experimental plan. For the same injectors, the return flow temperature during injection was tested over a period of 10-15 minutes, depending on the temperature stabilization time. A measured temperature value sustained for more than two minutes, with a deviation of ±5 °C, was considered a relevant result.

The test bench MM01 manufactured by Italian company Massimo Derosi is used for testing and shown in Figure 6.

Figure 6
Test bench MM01

Main assembly units of the test bench:

- Mechanical-hydraulic assembly block (component 1)
- Electronic control and monitoring units (component 2)

Key technical specifications:

- Drive system: Siemens 3kW electric motor
- Measurement apparatus: Calibrated beakers with measurement tubes (range: 0-100 ml)
- Fluid reservoir: 40-liter capacity test liquid tank

A correlation was established by comparing the values of the pressure drop time and the return flow temperature of the fuel injector, which is graphically represented in Figure 7.

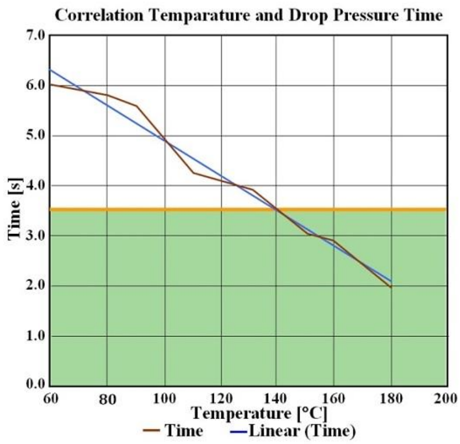

Figure 7

Graphical Representation of Correlation.

The shaded area in the graphical representation of the correlation in Figure 7 indicates the threshold value of work capacity loss, i.e., critical temperature. By measuring the return fuel temperature in this way, the degree of wear on the contact surfaces of the fuel injector can be indirectly determined. The main characteristic of the temperature sensor is its range of 0-200°C, 4-20mA, G1/4, type PT 100, integrated into the test bench.

Conclusions

Fuel injectors, as vital components of injection systems that significantly contribute to better utilization of fuel thermal energy in motor vehicles (locomotives, automobiles, heavy-duty trucks…), directly affect sustainable development at both national and international levels. As the degradation process of its contact surfaces accelerates, the period of proper operation (the service life) of fuel injectors decreases. If fuel injectors with damaged contact surfaces are not replaced with new ones in a timely manner, fuel consumption increases and the combustion process becomes inferior due to incomplete combustion. These effects are reflected in increased environmental pollution and reduction of natural energy resources. Based on original theoretical and experimental research, this paper identifies the parameters that have the greatest impact on the rate of surface degradation development of contact surfaces, and consequently on the rate of fuel injector service life decline.

and the temperature of return flow in the fuel injector system.

Significant reduction of Surface hardness of contact surfaces has the greatest influence, followed by clearance, roughness, and to a somewhat lesser extent, fluid temperature.

The detailed analysis conducted in this paper revealed the interdependence between the duration of pressure decrease ecological and energy crisis can be achieved by increasing the quality of contact surfaces of fuel injectors during their design, and timely replacement of worn parts with new or repaired components. By identifying the most influential parameters on the generation of surface damage on contact surfaces, a path has been paved for future research in the field of fuel injector service life assessment.

The results obtained in this work can be used by manufacturers of fuel consumption regulation systems as guidelines for developing new generations of fuel injectors.

Reference

[1] A. Kagramanian, P. Stankevich, D. Aulin and A. Basov, "Efficiency improvement of locomotive-type diesel engine operation due to introduction of resource-saving technologies for cleaning diesel and diesel locomotive systems," *Procedia Computer Science,* Vol. 149, pp. 264-273, 2019

[2] H. Valera, D. Kumar and A. K. Agarwal, "Evaluating the effect of variable methanol injection timings in a novel co-axial fuel injection system equipped locomotive engine," *Journal of Cleaner Production,* Vol. 349, p. 131452, 2022

[3] L. Plotnikov and N. Grigoriev, "Modernization of the Mechanical Fuel System of a Diesel Locomotive Engine through Physical and Numerical Modeling," *Energies,* Vol. 14, p. 8554, 2021

[4] V. Markworth, S. Fritz and G. Cataldi, "The Effect of Injection Timing, Enhanced Aftercooling, and Low-Sulfur, Low-Aromatic Diesel Fuel on Locomotive Exhaust Emissions," *Engineering for Gas Turbines and Power,* Vol. 114, No. 3, pp. 488-495, 1992

[5] L. Minghai, C. Hongjiang, W. Juan and G. Ying, "Improvement of fuel injection system of locomotive diesel engine," *Journal of Environmental Sciences,* Vol. 21, pp. S139-S141, 2009

[6] B. Jayashankara and V. Ganesan, "Effect of fuel injection timing and intake pressure on the performance of a DI diesel engine – A parametric study using CFD," *Energy Conversion and Management,* Vol. 51, No. 10, pp. 1835-1848, 2010

[7] T. Krogerus, M. Hyvonen and K. Huhtala, "A Survey of Analysis, Modeling, and Diagnostics of Diesel Fuel Injection Systems," *Journal of Engineering for Gas Turbines and Power,* Vol. 138, No. 8, p. 081501, 2015

[8] B. Mohan, W. Yang and S. K. Chou, "Fuel injection strategies for performance improvement and emissions reduction in compression ignition engines—A review," *Renewable and Sustainable Energy Reviews,* Vol. 28, pp. 664-676, 2013

[9] T. Kato, K. Tsujimura, M. Shintani, T. Minami and I. Yamaguchi, "Spray Characteristics and Combustion Improvement of D. I. Diesel Engine with High Pressure Fuel Injection," SAE Technical Paper 890265, 1989

[10] G. Tripathi, S. Nag, A. Dhar and D. Patil, "Fuel Injection Equipment (FIE) Design for the New-Generation Alternative Fuel-Powered Diesel Engines," in *Prospects of Alternative Transportation Fuels*, 2018, pp. 387-405

[11] J. Desantes, S. Molina, J. Benajes and C. Gonzalez, "The modification of the fuel injection rate in heavy-duty diesel engines. Part 1: Effects on engine performance and emissions," *Applied Thermal Engineering,* Vol. 24, No. 17-18, pp. 2701-2714, 2004

[12] S. Lee, C. Kim, J. Lee and J. Kim, "Diesel injector nozzle optimization for high CNG substitution in a dual-fuel heavy-duty diesel engine," *Fuel,* Vol. 262, p. 116607, 2020

[13] Y. Yoshihisa, K. Mori, H. Kamikubo, S. Kohketsu, K. Mori and T. Kato, "Application of Common Rail Fuel Injection System to a Heavy Duty Diesel Engine," *SAE International Journal of Engines,* Vol. 103, pp. 1977-1988, 1994

[14] K. Svensson, C. Kim, P. Seiler, G. Martin and C. Koci, "Performance and Emission Results from a Heavy-Duty Diesel Engine with Ducted Fuel Injection," *SAE Technical Paper,* 2021

[15] G. Zhang, X. Qiao, X. Miao, J. Hong and J. Zheng, "Effects of highly dispersed spray nozzle on fuel injection characteristics and emissions of heavy-duty diesel engine," *Fuel,* Vol. 102, pp. 666-673, 2012

[16] T. Lahde, t. Ronkko, M. Happonen, C. Soderstrom, A. Virtanen, A. Solla, M. Kyto, D. Rothe and J. Keskinen, "Effect of Fuel Injection Pressure on a

Heavy-Duty Diesel Engine Nonvolatile Particle Emission," *Environmental Science & Technology,* Vol. 45, No. 6, pp. 2504-2509, 2011

[17] K. Tanabe, S. Kohketsu and S. Nakayama, "Effect of Fuel Injection Rate Control on Reduction of Emissions and Fuel Consumption in a Heavy Duty DI Diesel Engine,," *SAE Technical Paper 2005-01-0907,* 2005

[18] R. R. Mallepally, B. A. Bamgbade, A. J. Rowane, H. B. Rokni, M. S. Newkirk and M. A. McHugh, "Fluid properties at high pressures and temperatures: Experimental and modelling challenges," *The Journal of Supercritical Fluids,* Vol. 134, pp. 33-40, 2018

[19] Z. Liu and A. Munnannur, "Future Diesel Engines," in *Design and Development of Heavy Duty Diesel Engines*, Springer, Singapore, 2020, pp. 887-914

[20] W. Knecht, "Diesel engine development in view of reduced emission standards," *Energy,* Vol. 33, No. 2, pp. 264-271, 2008

[21] D. Pierce, A. Haynes, J. Hughes, R. Graves, P. Maziasz, G. Muralidharan, A. Shyam, B. Wang, R. England and C. Daniel, "High temperature materials for heavy duty diesel engines: Historical and future trends," *Progress in Materials Science,* Vol. 103, pp. 109-179, 2019

[22] K. Yoon Seong, E. J. Han and S. Y. Sohn, "Demand Forecasting for Heavy-Duty Diesel Engines Considering Emission Regulations," *Sustainability,* Vol. 9, No. 2, p. 166, 2017

[23] C. J. Stephen, "Developing Diesel Engines to Meet Ultra-low Emission Standards," SAE Technical Paper 2005-01-3628, 2005

[24] G. Di Blasio, C. Beatrice, G. Belgiorno, F. C. Pesce and A. Vassallo, "Functional Requirements to Exceed the 100 kW/l Milestone for High Power Density Automotive Diesel Engines,," SAE Int. J. Engines, 2017

[25] A. Boretti, "Hydrogen internal combustion engines to 2030," *International Journal of Hydrogen Energy,* Vol. 45, No. 43, pp. 23692-23703, 2020

[26] X. Sun, Z. Li, W. Xiaolin and C. Li, "Technology Development of Electric Vehicles: A Review," *Energies,* Vol. 13, No. 1, p. 90, 2020

[27] S. Fischer and S. K. Szurke, "Detection Process of Energy Loss in Electric Railway Vehicles," *Facta Universitatis Series Mechanical Engineering,* Vol. 21, No. 1, pp. 081-099, 2023

[28] E. Agenjos, A. Gabaldon, F. G.Franco, R. Molina, S. Valero and M. Ortiz, "Energy efficiency in railways: energy storage and electric generation in

diesel electric locomotives," in *20th International Conference and Exhibition on Electricity Distribution (CIRED 2009)*, Prague, 2009

[29] B. Nikolic, S. Markovic, N. Petrovic, D. Marinkovic and V. Jovanovic, "Biodiesel and feedstocks - possibilities and characteristics: A review," *Thermal Science 2025 OnLine-First,* p. 58, 2025

[30] J. Doric, N. Nikolic, S. Galambos, D. Feher and B. Nikolic, "Innovative Design Strategy for an Internal Combustion Engine with Improved Output Characteristics," *Facta Universitatis, Series: Mechanical Engineering,* 2025

[31] C. Richard, "Tribological Coatings for High-Temperature Applications," *Encyclopedia of Tribology, Sprinnger,* pp. 3778-3787, 2013

[32] I. Gritsuk, E. Zenkin E.Y., N. Bulgakov, A. Golovan, I. Kuric, V. Mateichyk, M. Saga, V. Vychuzhanin, R. Symonenko, E. Rabinovich, V. Pavlenko and D. Pohorletskyi, "https://www.saecarolina.org/," 10 September 2018 [Online] Available: https://www.sae.org/publications/technical-papers/content/2018-01-1773/ [Accessed 09 November 2018]

[33] H. Thong Duc, T. H. Binh Thanh, M. H. Thien Quoc, T. Phat Tan and P. Minh Quang, "An experimental investigation on the performance of a single cylinder diesel engine at various partial loads," *Transportation Engineering,* Vol. 18, p. 100288, 2024

[34] V. J. Macián, R. Payri, B. Tormos and L. Montoro, "Applying analytical ferrography as a technique to detect failures in Diesel engine fuel injection systems," *Wear,* Vol. 260, No. 4-5, pp. 562-566, 2006

[35] P. Tomas, C. Ladislav, Š. Petr and R. Novak, "Tribological characteristics of CrCN coatings at elevated temperature," *Vacuum,* Vol. 80, No. 1-3, pp. 113-116, 2005

[36] C. Zishan, C. Yu, D. Dachao, Y. Qing and H. Miao, "Tribological performance of SiC coating for carbon/carbon composites at elevated temperatures," *Ceramics International,* Vol. 44, No. 10, pp. 11233-11238, 2018

[37] L. Chen, J. Paulitsch, Y. Du and P. H. Mayrhofer, "Thermal stability and oxidation resistance of Ti–Al–N coatings," Vol. 206, pp. 2954-2960, 2012

[38] J. Turner, D. Sykes, G. de Sercey, V. Stetsyuk, M. Gold, R. Pearson and C. Crua, "A Quantitative Analysis of Nozzle Surface-bound Fuel for Diesel Injectors," in *28th Conference on Liquid Atomization and Spray Systems*, Valencia, 2017

[39] G. Kökkülünk, A. Parlak, E. Bağci and Z. Aydin, "Application of Taguchi Methods for the Optimization of Factors Affecting Engine Performance and

Emission of Exhaust Gas Recirculation in Steam-injected Diesel Engines," *Acta Polytechnica Hungarica,* Vol. 11, No. 5, pp. 95-107, 2014

[40] J. Antony, D. Perry, C. Wang and M. Kumar, "An application of Taguchi method of experimental design for new product design and development process," *Assembly Automation,* Vol. 26, No. 1, pp. 18-24, 2006

[41] N. C. Fei, N. M. Mehat and S. Kmaruddin, "Practical Applications of Taguchi Method for Optimization of Processing Parameters for Plastic Injection Moulding: A Retrospective Review," *International Scholarly Research Notices,* Vol. 2013, 2013

[42] W. Vincent H., "Optimization of diesel engine parameters using Taguchi method and design of evolution," *Journal of the Brazilian Society of Mechanical Sciences and Engineering,* Vol. 34, pp. 423-428, 2012

[43] S. Xiao, W. Sun and J. Du, "Application of CFD, Taguchi Method, and ANOVA Technique to Optimize Combustion and Emissions in a Light Duty Diesel Engine," *Mathematical Problems in Engineering,* Vol. 2, pp. 1-9, 2014

[44] T. Ahn, J. Heo, S. Lee, H. Jung, J. Kim and H. Yi, "Fatigue Life Analysis of a Railway Bearing Using Taguchi Method," *International Journal of Computational Methods and Experimental Measurements,* Vol. 5, No. 5, pp. 733-740, 2017

[45] Y. Yang and C. Yu, "Prediction models based on multivariate statistical methods and their applications for predicting railway freight volume," *Neurocomputing,* Vol. 158, pp. 210-215, 2015

[46] L. Ezsias, R. Tompa and S. Fischer, "Investigation of the Possible Correlations between Specific Characteristics of Crushed Stone Aggregates," *Spectrum of Mechanical Engineering and Operational Research,* Vol. 1, No. 1, pp. 10-26, 2024

[47] S. Fischer, "Investigation of the Settlement Behavior of Ballasted Railway Tracks Due to Dynamic Loading," *Spectrum of Mechanical Engineering and Operational Research,* Vol. 2, No. 1, 2025

[48] S. Subramani and R. Kumar Babu, "Application of an enhanced Taguchi method for simultaneous reduction of smoke and NOx emissions using oxygenated additives and retarded injection timing in a stationary diesel engine," *Journal of the Brazilian Society of Mechanical Sciences and Engineering,* Vol. 38, pp. 1893-1906, 2016

[49] R. Fisher, "The Arrangement of Field Experiments," *Journal of the Ministry of Agriculture,* Vol. 33, pp. 503-515, 1926

[50] D. Janković and M. Ristivojević, "Primena plana eksperimenta (DOE) na reparaciju ubrizgača goriva," *Zbornik Međunarodnog kongresa o procesnoj industriji – Procesing,* pp. 1-7, 1 april 2017

[51] J. Stanić, M. Kalajdžić and R. Kovačević, Merna tehnika u tehnologiji obrade metala rezanjem, Belgrade: Građevinska knjiga, 1983