Evaluation of regenerative capabilities of piezoelectric fuel injectors

Ocena możliwości regeneracyjnych piezoelektrycznych wtryskiwaczy paliwa

Tomasz Stoeck

Dr inż.

Zachodniopomorski Uniwersytet Technologiczny w Szczecinie, Wydział Inżynierii Mechanicznej i Mechatroniki, Katedra Eksploatacji Pojazdów Samochodowych

ORCID: 0000-0002-4286-2747
tstoeck@wp.pl

Abstract: The article presents the issues related to the regeneration of injectors with piezoelectric actuators, taking into account existing technological constraints and the availability of original spare parts. The range of required maintenance operations among leading manufacturers of fuel systems was compared, as well as the types of diagnostic tests conducted in separate laboratory facilities. Examples of measuring devices, which should be considered as standard and optional equipment in workshops operating in this sector, were provided. Using the results of our own research, it was demonstrated that the regeneration process can be effectively carried out, even when it is necessary to expand existing procedures.

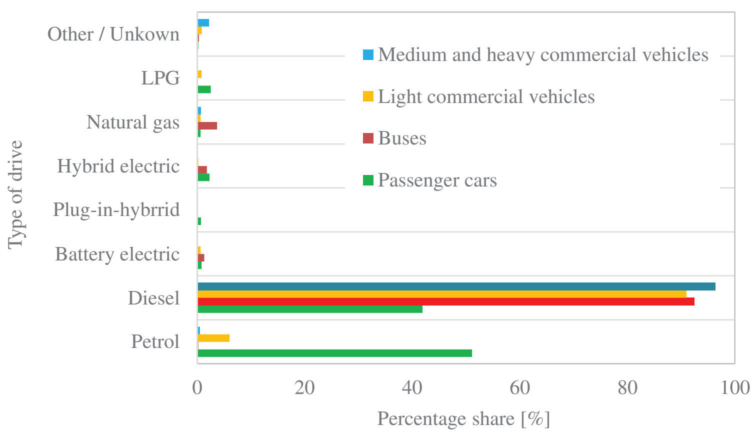
Keywords: *Piezoelectric fuel injectors; Diagnostic process; Regeneration*

Streszczenie: W artykule przedstawiona została problematyka regeneracji wtryskiwaczy z siłownikiem piezoelektrycznym, uwzględniając istniejące ograniczenia technologiczne i dostępność do oryginalnych części zamiennych. Porównano zakres wymaganych czynności obsługowych u czołowych producentów aparatury paliwowej, jak również rodzaje testów diagnostycznych przeprowadzanych na odrębnych stanowiskach laboratoryjnych. Podano przykłady urządzeń pomiarowych, które powinny stanowić standardowe i opcjonalne wyposażenie warsztatów działających w tym sektorze usług. Na przykładzie badań własnych wykazano, że proces regeneracji może być skutecznie prowadzony, nawet przy konieczności rozszerzenia istniejących procedur.

Słowa kluczowe: *Wtryskiwacze piezoelektryczne; Proces diagnostyczny; Regeneracja*

Introduction

In recent years, there has been increased interest in diversifying the fleet of motor vehicles used in transportation and commercial purposes. This is mainly due to the introduction of very strict emission standards, as well as technological advancements in the area of alternative propulsion sources. However, the decarbonization of this sector is progressing very slowly, and it is difficult to expect a radical change in the near future. For example, in European Union countries, the combined share of commercial vehicles equipped with compression ignition engines is 93.3% (Figure **1**) [2]. The majority of these vehicles use common rail fuel systems, which have displaced other fuel delivery systems due to their optimal fuel injection process shaping, thereby ensuring proper fuel-air mixture preparation and combustion process [1, 11, 12]. Subsequent generations of these systems have significantly improved their dynamic parameters, as well as achieved tangible benefits in reducing fuel consumption, noise emissions, and harmful substances [10, 18, 19]. However, meeting these requirements has necessitated the use of piezoelectric injectors gradually replacing solutions with traditional electromagnetic coils, allowing for more flexible control of multiphase fuel atomization and



1*. Types of vehicle propulsion systems in European Union countries*
Source: own study based on [2]

adaptation to increasingly higher operating pressures [4, 5, 8].

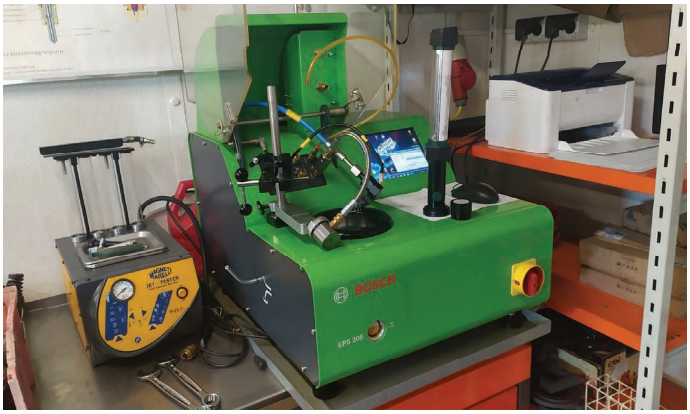
Transportation services are associated with the costs of operating a vehicle fleet, which directly impact the profitability of the business [3]. As a result, there is a growing interest in the regeneration of components of fuel injection systems, as this process allows for restoring their factory performance parameters. Among the undeniable advantages are also the relatively short vehicle downtime, warranty provided by the service workshop, and significant reduction in expenses compared to the use of new products [16]. For these reasons, the article presents the contemporary repair possibilities for piezoelectric injectors, which have not been supported by manufacturers for a long time. In the absence of original spare parts, their maintenance was limited to cleaning, diagnostic testing, and, if necessary, replacing the nozzle (needle with a sprayer) for selected reference numbers. Currently, the situation has somewhat improved, mainly due to specially dedicated measurement equipment and partial access to substitutes.

Contemporary diagnostic stations

All examinations of fuel systems that require the disassembly of their executive components from the engine are classified as invasive methods. Among these methods, the most precise and reliable way to control the technical condition of injectors is through tests conducted on specially dedicated test benches. These are universal station devices equipped with single or multiple measurement circuit systems. They are available in compact versions (Figure **2**), as well as modular constructions (Figure **3**), allowing for the installation of additional equipment in line with the workshop's profile and capabilities. The benches are equipped with necessary adapters and connections for the installation of hydraulic and electrical lines to the injector. This enables not only comprehensive testing but also internal cleaning, which involves a thermochemical flushing process with high-pressure and elevated temperature detergent.

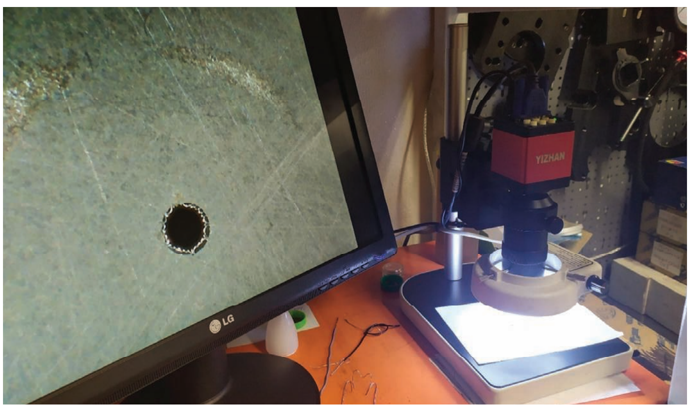
The technical condition is assessed based on approved procedures, including electrical, leak, nozzle opening pressure tests, etc. Any deviations detected in these tests immediately result in the discontinuation of the initial testing phase. In the case of positive results, flow measurements are conducted at various activation times and operating pressures. Typically, these measurements are performed in automatic cycles or less frequently with manual adjustments, where the quantity of individual doses and corresponding return flows are checked at several operating points, thus simulating changing engine load conditions. The results are compared with the manufacturer's database available from the test device, then recorded and printed as a measurement report. Exceeding the limit values constitutes the basis for disassembling the injector into its components.

Examinations under high magnification aim to determine the degree of wear and detect any potential malfunctions in the components that are part of the executive and control assemblies. These examinations are carried out on separate laboratory stations equipped with an optical stereoscopic microscope capable of digital image recording or an industrial camera (Figure **4**). In standard procedures, it



2. Compact test bench EPS 205 (Bosch)
Source: own study

3. Modular test station STPIW-3 (Autoelektronika Kędzia)
Source: own study



4. Microscopic inspection using Yizhan 13MP HDMI VGA industrial camera
Source: own study

5. Electrical measurements of Denso G2P injector on Mega Tester V3 probe
Source: own study

is assumed that visual inspections precede the stages of cleaning individual components in ultrasonic cleaners and their thorough drying with compressed air. However, this sequence may change in situations where there is a reasonable suspicion of the presence of metal filings that enter the fuel system from a faulty fuel pump.

Another group comprises optional testing equipment that assists the fundamental diagnostic process. In the case of piezoelectric injectors, probes are extremely useful as they enable expanded measurements of the actuator and precise determination of its technical condition (Figure **5**). Another example is leak testers, which are useful for detecting leaks within the overflow pipe and nozzle (Figure **6**). By applying a control pulse from an additional device, it is also possible to assess fuel atomization quality, nozzle opening time, etc.

The course of the injector regeneration process

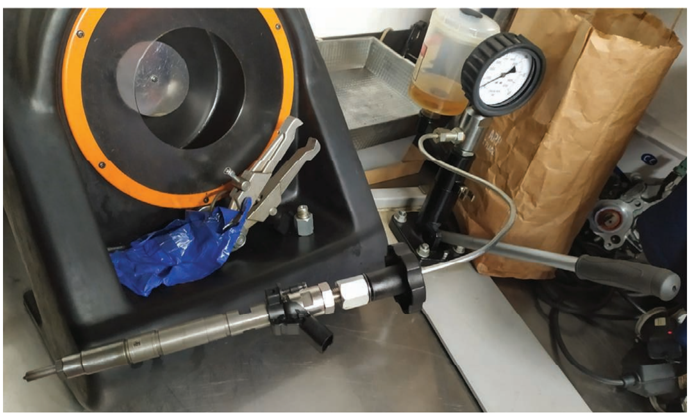
Table **1** presents a comparison of diagnostic and service procedures carried out in the process of regeneration of piezoelectric injectors. It can be observed that the procedures of individual manufacturers are similar to each other and differ in a few aspects. First and foremost, Siemens VDO Continental products require the adjustment of the air gap, referred to as GAP, located between the actuator and the hydraulic transducer (Figure **7**). This is due to their specific construction, as the stack of crystals is not placed inside the main body but is attached to it using a nut. On the other hand, the optional revitalization process, involving the removal of short circuits between individual layers, is not conducted for Delphi products. Unlike other manufacturers, Denso injectors, in addition to assigning new codes and entering them into the engine control module, require an additional calibration of zero doses. During this time, the system performs self-diagnostics to check the fuel delivery method at different operating pressures and actuation times.

Tab. 1. *Comparison of diagnostic and service procedures among selected manufacturers*

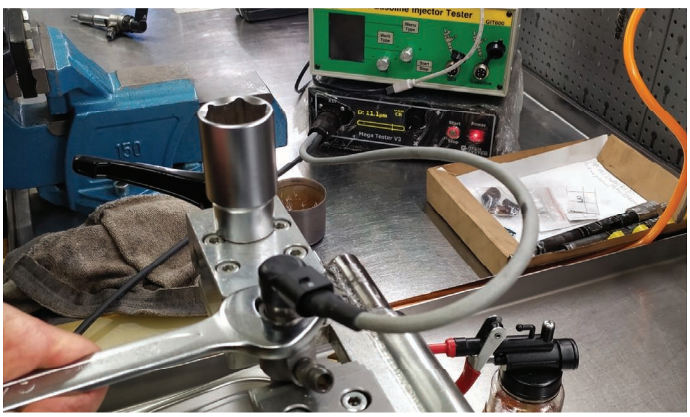
Type of activity	Injector manufacturer			
	Bosch	Siemens VDO Continental	Denso	Delphi
Inspection and verification	•	•	•	•
Electrical testing	•	•	•	•
Internal cleaning (thermochemical)	•	•	•	•
Leakage testing	•	•	•	•
Spray pattern testing	•	•	•	•
Preliminary flow testing	•	•	•	•
Disassembly	•	•	•	•
Ultrasonic cleaning of parts	•	•	•	•
Microscopic inspection	•	•	•	•
Replacement of parts with new ones	•	•	•	•
Assembly	•	•	•	•
Air gap adjustment (GAP)		•		
Main flow testing	•	•	•	•
Crystal stack revitalization (optional)	•	•	•	
Injector coding	•	•	•	•
Zero calibration on the engine			•	

Source: own study

Unfortunately, access to specialized equipment and dedicated tools does not always translate into the effectiveness of the regeneration process. The main problem is the lack of spare parts (Table **2**). Firstly, most manufacturers do not offer the replacement of the piezoelectric stack, which is why the technology behind this process has not been made available. An exception to this is the substitutes for Siemens VDO Continental injectors, which can be obtained in the primary market. Such actuators are referred to as solenoids, as their disassembly method is analogous to electromagnetically controlled constructions (Figure **8**). Secondly, the remaining executive components are completely disassemblable, allowing for thorough cleaning in ultrasonic baths and microscopic inspections. However, identifying damage outside of the nozzle (needle and atomizer) becomes problematic in the case of Denso and Delphi products. In individual cases, used parts can be used, which come from injectors previously deemed irreparable, usually due to crystal damage. These parts are often left by customers themselves or obtained through other means, such as from collaborating auto repair shops, pur-



6. *Injector leak testing with Bass BP-3605 tester*
Source: own study



7. *Adjustment of the air gap (GAP) in Siemens VDO Continental injectors*
Source: own study

Tab. 2. *Comparison of parts replacement capabilities among selected manufacturers*

Type of activity	Injector manufacturer			
	Bosch	Siemens VDO Continental	Denso	Delphi
Nozzle	•	•	•	•
Valve	•	•		
Hydraulic amplifier	•	•		
Piezoelectric crystal stack		•		

Source: own study

Tab. 3. *Results of the preliminary tests*

Type of parameter	Nominal range	Result
Electrical measurements		
Piezo actuator resistance, R [kΩ]	150-210	182
Piezo actuator capacitance, C [μF]	1.5-3.3	2.24
Flow measurements		
Maximum Load, VL [ml/min]	46.2±6.5	37.9
Emission Point, EM [ml/min]	18.7±4.3	16.2
Pre-injection, VE [ml/min]	1.8±1.5	0.9
Idle, LL [ml/min]	3.1±2.7	2.2

Source: own study

Tab. 4. *Results of the main tests*

Type of parameter	Nominal range	Result
Maximum Load,		
VL [ml/min]	46.2±6.5	43.9
Emission Point,		
EM [ml/min]	18.7±4.3	19.2
Pre-injection,		
VE [ml/min]	1.8±1.5	1.7
Idle,		
LL [ml/min]	3.1±2.7	3.9

Source: own study

8*. Disassembled injector actuator 2.3 PCR from Siemens VDO Continental*
Source: own study

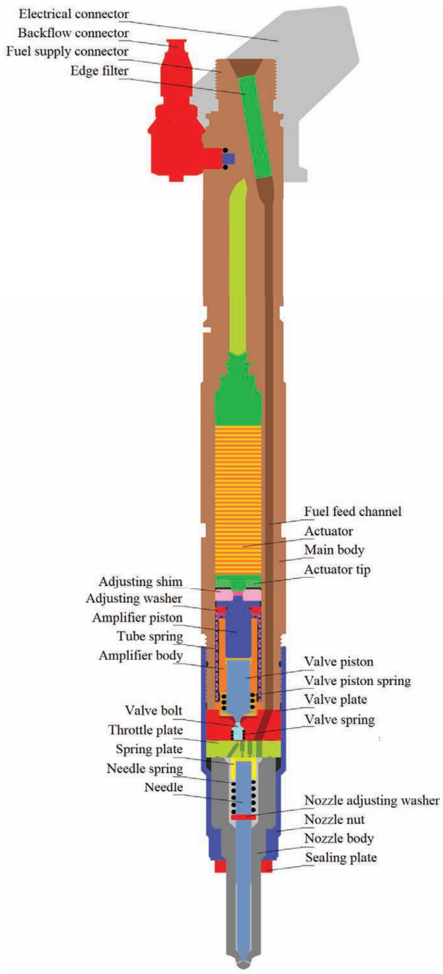
chased online in the secondary market, etc. However, this process, referred to in the literature as cannibalization, is difficult to consider as a comprehensive solution when considering the actual scale of demand for regeneration services.

Example of own research

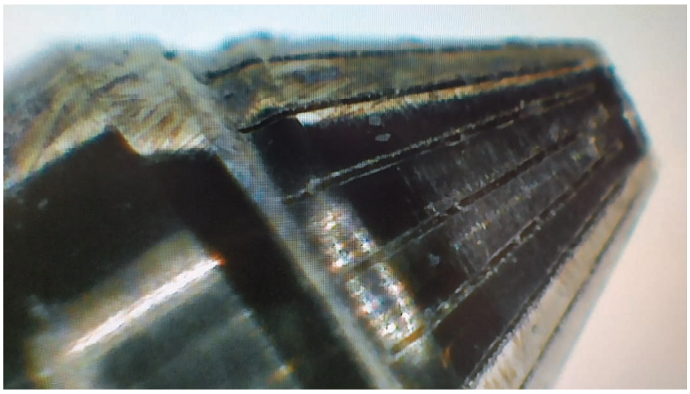
Based on years of laboratory-workshop practice, it is evident that even the availability of spare parts may prove insufficient for a successful regeneration process. Prolonged usage leads to a decrease in the initial extension of the stack and its impact on the actuating components. This is due to the degradation of crystal properties resulting from the aging process [6, 14, 15]. As an example, our own study involved the Bosch CRI3-16 injector, which was disassembled from a 2.0 dCi Nissan X-Trail engine with a mileage of 322,000 km. Figure **9** illustrates its internal structure, highlighting the key control and actuating elements.

Electrical tests ruled out permanent failure of the piezoelectric actuator, as its resistance and capacitance fell within the manufacturer's specified ranges. However, preliminary flow tests revealed an incorrect value of the full-load dose VL (Table **3**). Therefore, a decision was made to disassemble the components for detailed microscopic inspections. Corrosion was observed on most fuel-contacting elements, and traces of abrasive wear were identified on selected working surfaces (Figure **10**). As a result, the complete nozzle assembly, valve, and hydraulic transducer were replaced.

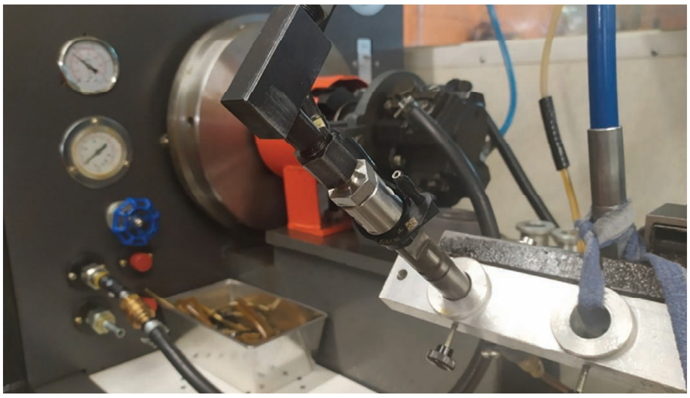
The performed actions proved to be insufficient as the fuel delivery was



9*. Bosch CRI3-16 fuel injector design*
Source: own study based on [13, 17]



10. Example of corrosion and needle wear
Source: own study



11. Testing of the Bosch CRI3-16 injector on the 12PSB test bench with the Stardex set. Source: own study

still not correct. It was decided that intervention in the hydraulic converter would be necessary to ensure the required length compensation. In the absence of support from the manufacturer, who does not provide repair technology or specific selection group shims, the surface of the front face of the element was ground down by 0.25 mm. From the data presented in Table **4**, it can be concluded that the regeneration of the tested injector was successful, as the main flow tests yielded results within the nominal ranges (Figure **11**). Furthermore, the applied adjustment method had an impact on increasing the values of all fuel doses, not just at the intended operating point. In this regard, the decision to replace the valve group is also significant, as the sealing integrity of the valve group was compromised during the long-term operation of the injector.

In injectors with lower mileage, there is also a possibility to adjust the stack extension in the final coding phase. This process, similar to flow testing on the test bench, is conducted automatically. Shifting the operating range only requires finding a higher threshold voltage at which the crystal reaction and its interaction with the main control valve occur [7]. Consequently, the obligatory assignment of a new ISA code (German: Injektor-Spannungs-Abgleich) serves as a corrective action, supplementing the information regarding fuel metering in the IMA code (German: Injektor-Mengen-Abgleich) [9].

Conclusion

Undoubtedly, a significant benefit of regeneration is cost reduction, which, when combined with the assurance of required quality, presents an interesting alternative to brand-new products. In a broader context, this process plays a crucial role in shaping the image and pro-environmental policy, constituting an essential element of a closed-loop economy. This is particularly important regarding high-pressure fuel injection systems, considering the dominant presence of vehicles equipped with compression-ignition engines in commercial transportation. For these reasons, it is highly significant to eliminate inhibiting barriers associated with the lack of crystal stack replacement technology and access to original spare parts. This will enable the regeneration of piezoelectric injectors to be conducted practically to its full extent, similar to what has been achieved with electromagnetically controlled solutions, which have undergone three repair stages over the years. The first step has already been taken, as devices are currently available in the market that enable comprehensive assessment of their technical condition and the performance of necessary diagnostic tests.

Currently, 4-pin injectors, such as the Bosch CRIN 4.2, have started to be repaired after their warranty period has expired. These systems are characterized by an additional hydraulic reinforcement called HADI (Hydraulically Amplified Diesel Injector), allowing them to deliver fuel at operating pressures of up to 270 MPa. They were introduced into heavy-duty vehicle engines to meet the most stringent emission regulations, further improve performance, and enhance fuel efficiency. Consequently, it can be expected that 3rd generation piezoelectric injectors, which are the main focus of this article, will receive significantly greater support from manufacturers, as well as increased utilization in commercial transportation.◀

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