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Tomasz STOECK

Combustion Engines
Polish Scientific Society of Combustion Engines

Enhanced diagnostics of common rail piezoelectric injectors using the box method

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The article presents one of the techniques of analytic geometry, referred to as the box method or the Minimum Bounding Rectangle (MBR) approach, which was applied in the diagnostics of a common rail piezoelectric injector. By extending the standard test procedure with a computational phase, it was possible to estimate the fuel dosing surface areas and compare them with reference values. It was demonstrated that the proposed method is particularly useful in situations where a clear assessment of the injector's technical condition is difficult to obtain. This approach eliminates the need for additional measurements during the active testing phase, without increasing the final costs or the time required for the regeneration process.

Key words: *common rail system, piezoelectric fuel injector, box method, regeneration process*

1. Introduction

For many years, test benches have been used for the precise assessment of the technical condition of common rail injectors. These are universal, stationary diagnostic stations where service tests are conducted according to strictly defined procedures. This is made possible by dedicated software as well as databases that are periodically updated by the manufacturers. Among the various test plans performed automatically, a key role in injector diagnostics is played by Injector Volume Metering (IVM) tests. These typically involve evaluating fuel injection at four operating points, corresponding to the following injection quantities: full-load, part-load (emission), pre-injection, and idle [8, 9, 11]. Additional diagnostic information is provided by the backflow values, which are especially useful in assessing the proper functioning of the valve group [6, 10]. The obtained results are compared against threshold ranges, i.e., the fuel delivery tolerances stored in the test bench memory, and are then printed as a measurement protocol.

Unfortunately, problematic cases sometimes occur in which injectors fail to operate correctly, even though they meet the requirements defined in the test plans. In extended diagnostics, the number of measurement points is typically increased, which raises costs and prolongs the experimental phase [1, 5]. For this reason, an entirely different approach was adopted, based on identifying hidden dysfunctions using computational methods. It was assumed that the reference points from the standard procedure would be located within a Cartesian coordinate system and then connected to form an irregular quadrilateral. A similar process was applied to a reference injector, which allowed for the estimation and comparison of the surface areas of the resulting figures. Discrepancies in the calculated areas served as the basis for evaluating the technical condition of the tested injector. Examples of this approach in practical applications have been presented in publications [17, 18, 20].

The proposed box method offers an interesting alternative to previously employed computational techniques based on classical Gaussian and Newton-Cotes formulas. The analytical process is sufficiently simple to be carried out manually, which makes it particularly suitable for use under typical workshop conditions. At the same time, repeatability and automation can be achieved in a digital environment, since the formulas implemented in a spreadsheet provide a ready-to-use tool for performing future analyses.

2. Methods

2.1. Test object

The study was conducted on a Siemens VDO Continental 2.3 PCR injector (part number 5WS40156), taken from a 2.0 TDCi engine of a Ford Galaxy vehicle with a mileage of 278,000 km.

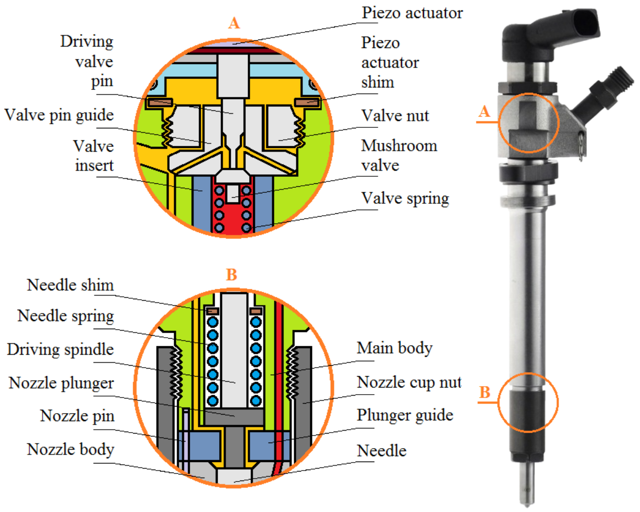

Fig. 1. Siemens VDO Continental PCR 2.3 fuel injector design [19]

This is a second-generation injector, operating at a maximum working pressure of 160 MPa [21]. In contrast to solutions offered by other manufacturers (e.g., Bosch, Denso), the piezoelectric actuator is positioned outside the main body, which allows for its straightforward replacement in the event of failure (Fig. 1). Moreover, this placement is also practically convenient, as it facilitates routine service operations, particularly: disassembly of the injector into individual components, ultrasonic cleaning, calibration, and reassembly after repair.

2.2. Test bench

The experimental phase was conducted on a Stardex Nova Ultima test bench, which included a simulator, flow meter, and a cooling, filtering, and damping module (Fig. 2). The test bench was complemented by a 12PSB drive table, as well as a PC-class computer with an Ubuntu Linux operating system installed.

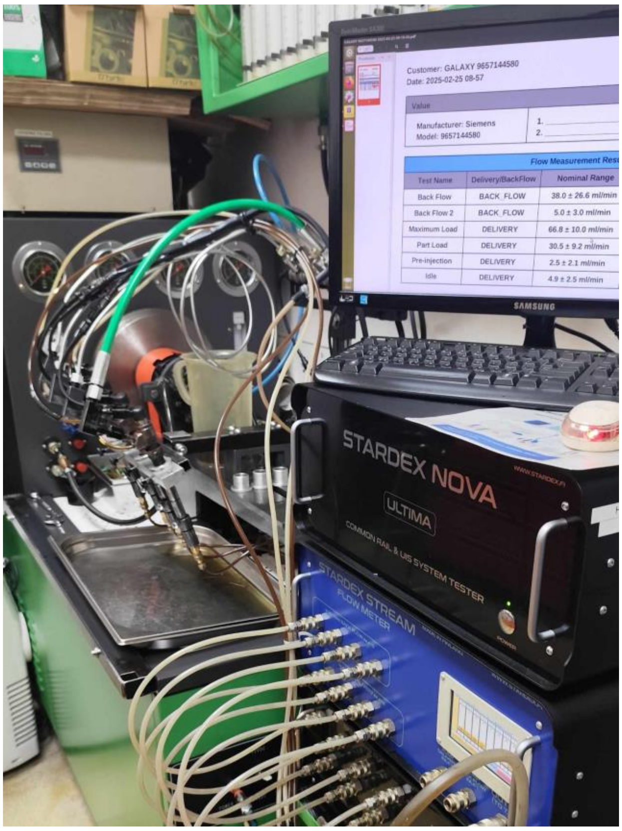

Fig. 2. General view of the Stardex Nova Ultima test bench

Additional equipment and tools were also used, which enabled the testing and comprehensive regeneration of the injector under investigation. The most important ones include:

– Mega Tester V3 electrical parameter measurement device
– Yizhan 13MP HDMI VGA industrial camera
– Bene YesWeCan 3L ultrasonic cleaner
– Facom E.316A200S torque wrench.

2.3. Research plan

Table 1 presents the test plan, which, in the measurement and operational parts, largely aligned with the manufacturer's procedure. The only exception was the comprehensive electrical parameter testing of the injector using the Mega Tester V3 device. Additionally, the extended diagnostics required the introduction of a computational phase, which was carried out on a station equipped with a PC-class computer. This computer is typically also used for visualizing and recording images transmitted from an industrial camera or laboratory microscope.

Table 1. Research plan with division into stages and workstations

Workplace	Stage I	Stage II
Mega Tester V3	Electrical test	Calibration
Stardex Nova Ultima	Internal cleaning	Main flow tests
	Preliminary flow tests	Injector coding
Personal computer	Calculation phase	Calculation phase
Tool stand	Disassembly into parts	Final acceptance
	Microscopic examination	
	Ultrasonic washing	
	Part drying	
	Parts exchange	
	Assembly	

2.4. Box method

In the Cartesian coordinate system, the points corresponding to the fuel delivery of the reference injector were located. After connecting them, an irregular quadrilateral with vertices 1-2-3-4 was obtained (Fig. 3). To calculate the area of the figure, the box method was applied, which involves embedding the figure in a rectangle with sides parallel to the coordinate axes and dividing the considered area into smaller parts [7, 15, 16]. The final result can be obtained from the following formula:

$$A_{VII} = A_{box} - A_{I} - A_{II} - A_{III} - A_{IV} - A_{V} - A_{VI} \quad (1)$$

The use of the box method, also referred to as the Minimum Bounding Rectangle (MBR), is practically convenient, as in the component calculations of AI-AVII, only elementary mathematical formulas for the area of a rectangle (length × width) and a right triangle (½ × base × height) are considered [3, 4, 23].

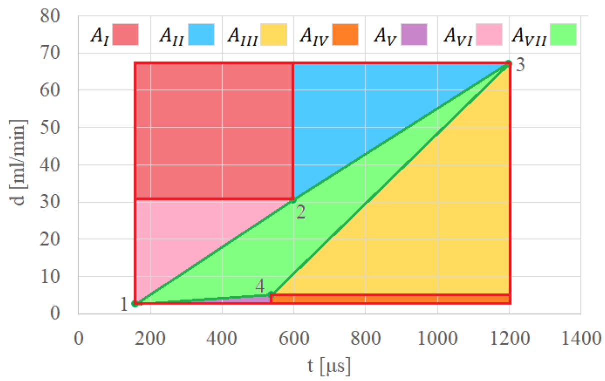

Fig. 3. Interpretation of the box method for the reference injector

Table 2 presents the results obtained for the input data, namely the nozzle opening times (t) and the corresponding fuel doses (d): pre-injection (1), part-load (2), full-load (3), idle (4).

Table 2. Results of surface area calculations for the reference figure

Input data						
Point	t			d		
1	160			2.5		
2	600			30.5		
3	1200			66.8		
4	540			4.9		
Calculation result						
A_{box}	A_{I}	A_{II}	A_{III}	A_{IV}	A_{V}	A_{VI}
66,872	15,972	10,890	20,427	1584	456	6160
A_{VII}						
11,383						

3. Analysis results and discussion

3.1. Preliminary tests

The injector testing began with comprehensive electrical measurements using the Mega Tester V3. Based on these measurements, the failure of the piezoelectric stack was ruled out, as the obtained values met the requirements specified by the manufacturer, i.e., capacitance C = 3.4 μF (min. 2.8 μF), resistance R = 186 kΩ (160–220 kΩ) [22]. Furthermore, no damage to the actuator insulation was found, and a positive result was obtained in the continuous load test under the operating voltage of U = 200 V [11] (Fig. 4). For these reasons, the injector was cleared for flow measurements (IVM) on the Stardex Nova Ultima test bench (Fig. 5).

Fig. 4. Correct result of the continuous load test

Table 3. Results of preliminary IVM flow tests

Test name	p_{inj} [MPa]	t [μs]	d [ml/min]
Fuel doses			
Pre-injection	80	160	[2.5 ±2.1] 0.7
Part load	120	600	[30.5 ±9.2] 25.1
Maximum load	160	1200	[66.8 ±10.0] 56.9
Idle	25	540	[4.9 ±2.5] 4.4
Fuel returns			
Test name	p_{inj} [MPa]	t [μs]	r [ml/min]
Back flow	135	810	[38.0 ±26.6] 11.7
Back flow 2	25	540	[5.0 ±3.0] 3.6

Tables 3 and 4 present the measurement and calculation results obtained during the preliminary test. Although the fuel doses fell within the manufacturer's specified ranges, their values deviated from the accepted reference patterns. This was especially the case for points 2` and 3`, which were obtained under part-load and full-load conditions. As a result, the area of the tested injector was not only shifted but also 20% smaller compared to the quadrilateral 1-2-3-4 (Fig. 6).

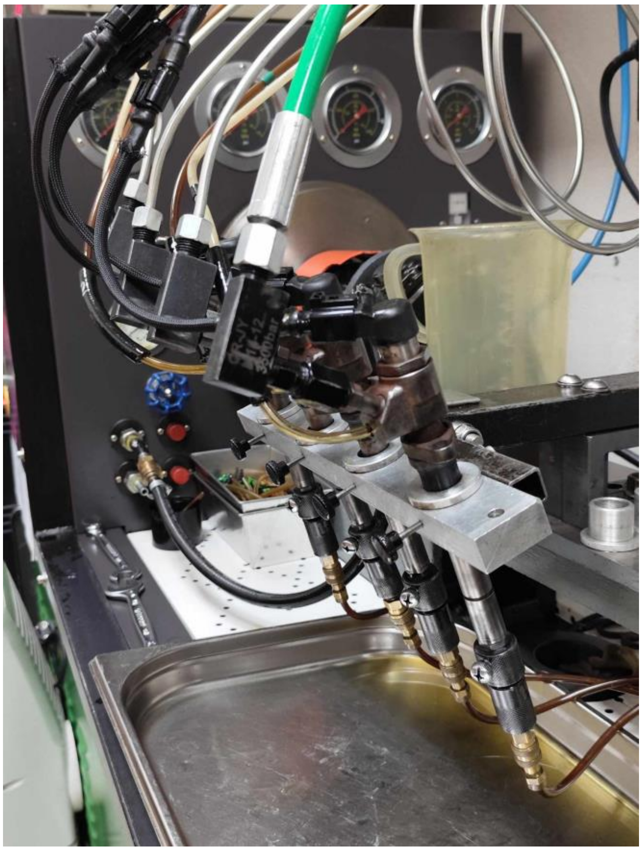

Fig. 5. Injector testing on the Stardex Nova Ultima test bench

Table 4. Results of surface area calculations for the figure 1`-2`-3`-4`

Input data						
Point	t			d		
1`	160			0.7		
2`	600			25.1		
3`	1200			56.9		
4`	540			4.4		
Calculation results						
A_{box}	A_I	A_{II}	A_{III}	A_{IV}	A_V	A_{VI}
58,448	13,992	9540	17,325	2442	703	5368
A_{VII}						
9078						

The cause can be attributed to the improper functioning of the precision pair (needle, nozzle), which, given the current operating conditions, should be replaced without delay [14]. It is also worth noting that the valve group operated correctly, maintaining its sealing regardless of the pressure set on the test bench. This is evidenced by the low values of return fuel flows.

Microscopic examinations revealed corrosion on many components that had direct contact with diesel fuel. Additionally, erosive wear was detected near the needle tip (Fig. 7). As a result, the decision to replace the precision pair was upheld, and the remaining components were directed for thorough cleaning in an ultrasonic cleaner. This process allows for the removal of deposits and contaminants that were not caught by the fuel filter. It is also possible to remove corrosion traces in cases where the pits are not extensive and are not deep [2, 13]. The piezoelectric actuator was excluded from this stage, as its insulation could have been permanently damaged.

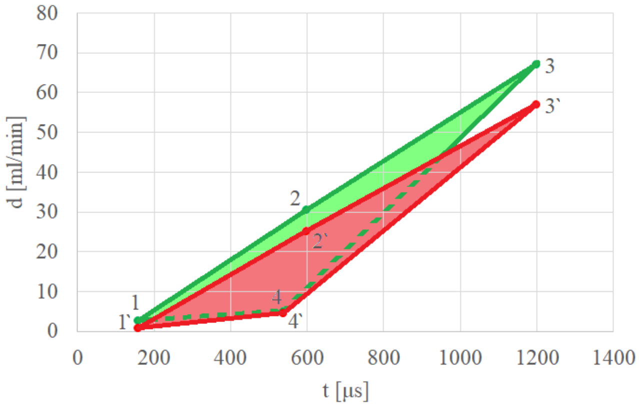

Fig. 6. Graphical interpretation of the results of preliminary tests

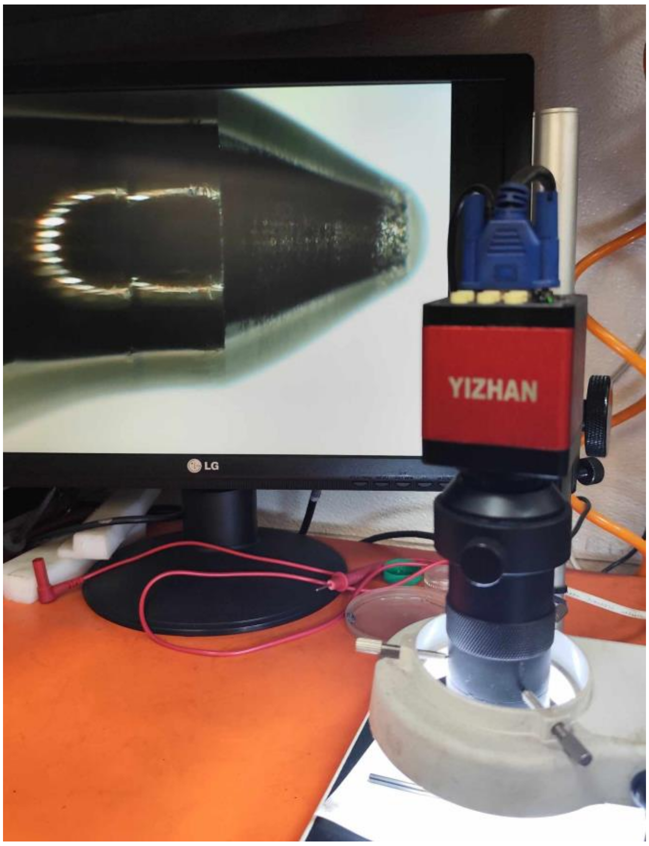

Fig. 7. Observation of corrosion traces and wear on the needle tip

To correct the fuel dosing by the injector, a shim from a lower selection group was used during the assembly of its upper part (Fig. 8). Additionally, the distance between the piezoelectric actuator and the valve pushrod was slightly reduced, setting the value of GAP = 1.7 µm. The calibration process using the Mega Tester V3 device is shown in Fig. 9.

Fig. 8. GAP calibration during the tightening of the piezoelectric actuator

3.2. Main tests

Tables 5 and 6 present a summary of the final results obtained in the main tests.

Table 5. Results of the main IVM flow tests

Test name	p_{inj} [MPa]	t [µs]	d [ml/min]
Fuel doses			
Pre-injection	80	160	[2.5 ±2.1] 1.8
Part load	120	600	[30.5 ±9.2] 31.2
Maximum load	160	1200	[66.8 ±10.0] 66.1
Idle	25	540	[4.9 ±2.5] 5.3
Fuel returns			
Test name	p_{inj} [MPa]	t [µs]	r [ml/min]
Back flow	135	810	[38.0 ±26.6] 13.4
Back flow 2	25	540	[5.0 ±3.0] 3.9

The regeneration process can be considered successful, as the surface areas of the tested and reference injectors were nearly identical, with a size difference of only 1.4% (Fig. 9). This improvement resulted from an increase in the individual fuel dose values compared to the initial condition, which affected the position of the quadrilateral vertices 1``-2``-3``-4``. At the same time, despite not replacing the valve group, the back fuel flow values remained very similar to those obtained in the preliminary test. It is also worth noting that the coding phase was carried out on the same test bench used for all IVM flow tests. This step is essential before the final installation of the injector in the engine.

Table 6. Results of surface area calculations for the figure 1``-2``-3``-4``

Input data						
Point	t		d			
1``	160		1.8			
2``	600		31.2			
3``	1200		66.1			
4``	540		5.3			
Calculation results						
A_{box}	A_{I}	A_{II}	A_{III}	A_{IV}	A_{V}	A_{VI}
66,872	15,356	10,470	20,064	2310	665	6468
A_{VII}						
11,539						

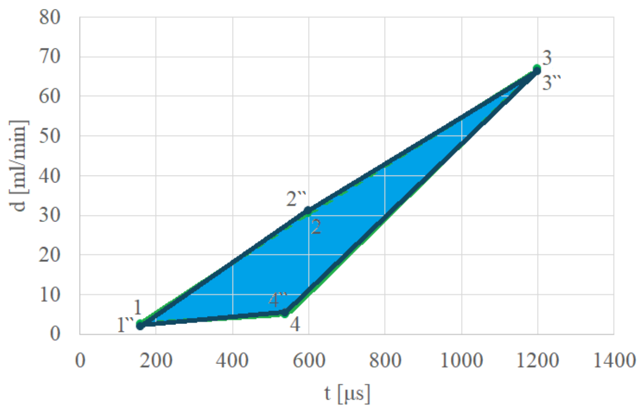

Fig. 9. Graphical interpretation of the results of the main tests

4. Conclusions

The proposed box method enables the use of advanced diagnostics for common rail injectors, whose operation raises concerns despite meeting the requirements set by the manufacturer. Its main advantages include:

1. The use of reference points eliminates the need for additional measurements during the experimental phase. As a result, the entire testing procedure is automated and does not require switching to manual mode or modifying the test bench software.
2. The positioning of the vertices affects the size of the surface areas of the analysed shapes and indicates possible causes of injector dysfunction.
3. The analytical process poses no significant difficulties, as elementary mathematical formulas are used in the calculations. Their correctness can be verified using other mathematical methods, such as Gauss or Newton-Cotes formulas.
4. In workshop and laboratory practice, cases were considered where 3 out of 4 vertices of the irregular quadrilateral were directly located along the sides of the rectangle. This allowed simplifying equation (1) due to a smaller number of components.
5. Input data for the calculations can come from any test bench where IVM flow tests are conducted.

It should be emphasized that the use of the box method becomes ineffective when the manufacturer's standard procedure assumes a greater number of measurement points. An example of this is the electromagnetic injectors from Delphi, which on the Stardex Nova Ultima test bench are checked for 15 fuel doses and 1 return fuel flow. This process is advanced and precise enough that the use of extended diagnostics becomes unnecessary.

It should also be noted that the calculated fuel delivery surface areas should be treated as purely hypothetical, as they may not reflect the actual performance of the injector outside the base (standard) operating points. Nevertheless, the proposed solution has proven applicable in practical settings, and the presented implementation method has no direct equivalent in the existing technical literature.

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All research was conducted at the Szczecin-based company AUTO NEXT SERWIS, which provided the specialized equipment and tools necessary for the injector regeneration process.

Nomenclature

A surface area of the quadrilateral (indices):
1-2-3-4 – reference
1`-2`-3`-4` – in preliminary tests
1``-2``-3``-4`` – in main tests

$A_{I\text{-}VII}$ surface areas of the box's components

A_{box} surface area of the box

d injection dosage

C piezo actuator capacitance

GAP space between the piezo actuator and the valve pusher

IVM injector volume metering

MBR minimum bounding rectangle

PC personal computer

PCR piezo common rail

p_{inj} injection pressure

R piezo actuator resistance

t nozzle opening time

TDCi turbo diesel common rail injection

U continuous load test voltage

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Tomasz Stoeck, DEng. – Faculty of Mechanical Engineering and Mechatronics, West Pomeranian University of Technology in Szczecin, Poland.

e-mail: *tstoeck@wp.pl*