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COMPUTER-AIDED DIAGNOSTICS OF INJECTION AND COMBUSTION PROCESSES IN ENGINES EQUIPPED WITH COMMON RAIL FUEL INJECTION

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Abstract

In earlier designs, the compression-ignition engine units were controlled by means of mechanical elements. They were levers, rods, springs, pawls, cams and others. The quality of such control did not ensure the required repeatability of control parameters in the fuel injection and combustion process. After the introduction of the standards limiting engine emissions of the limited exhaust components, the aforementioned engine control systems were not able to meet the requirements. The mechanical regulation of mechanical systems has been replaced by electronic control systems. It was the development of computer techniques and software that enabled design solutions of control systems for injection and combustion process parameters in engines with sufficient accuracy and repeatability of test results. The modern EDC (Electronic Diesel Control) control system, due to the computing power of microprocessors increased in recent years, enables meeting high requirements of modern Common Rail injection systems.

The article presents issues in the area of four thematic levels: the design and modernization of the engine, its operation, diagnostic problems in order to determine reasons of unit failures and bench-top methods for assessing the effectiveness of unit repairs as well as issues concerning alternative fuels.

Keywords: Diesel engine, alternative fuels, quick-changing parameters, injection process, combustion process, uniqueness of injection and combustion processes, diagnostics process.

1. INTRODUCTION

The use of computer-aided research together with the applied software occurs in diagnostics of engines in several areas. We can distinguish four basic tests related with one another in various ways. They are:

- tests on new engine designs diagnostics in new solutions of engine design;
- examining the technical condition of the engine in the operation proces including diagnostics;
- diagnostics of engine assemblies after their repair
- new alternative fuels [9].

For the last several decades, intensive, extensive research on the effects of the use of alternative fuels for compression ignition engines has also been observed. Vegetable fuels and their esters play a dominant role here. Since the beginning of the seventies of the last century, intensive diagnostic research on both the production and attempt to use plant fuels and their esters for compression – ignition (CI) engines has been undertaken. European countries tested not only methyl esters of fatty acids of RME rapeseed oil, but also other oils obtained from sunflower seeds and soybeans. These studies have been conducted on a large scale since 1989 at the Radom University of Technology under the author's supervision. However, this research problem was also dealt with in Germany, Austria, France, Italy and other countries. In the United States, the studies included soybeans, maize, and in Brazil and Argentina, sugar cane [4].

Currently, these studies have not been discontinued and they are being extended including new raw materials from seeds of: camellia, rubber, atrophy, jojoba, karanja grown in Mexico, Bolivia, Peru, Argentina, Paraguay, India, China and Japan [1, 7, 10, 13].

For several years, new technologies have also been observed as far as the use of waste animal fats and used consumable oils are concerned [1, 2, 5, 12].

Extensive research is also carried out concerning the use of waste from the pulp industry and algae cultivation on an industrial scale [2]. It should be remembered here that since 2020, the European Union Directive has been in force in the scope of the annual consumption of 10% of biofuels in relation to the fuels consumed. Biofuels were mentioned here, because research on their application for engines requires highly developed methods of modelling the injection and combustion processes in engines [3, 14]. Currently in Poland, for compression ignition engines, diesel oil with the addition of 7% (v/v) of rapeseed oil esters or FAME [20, 21] is sold in fuel stations.

This was due to the depletion of oil resources, geopolitical considerations and global warming. The introduction of increasingly stringent standards in terms of emissions of limited exhaust gas components in many countries force engine and fuel manufacturers to use the optimization of combustion processes in engines as well as new technologies in fuel production.

The planned modernization of the engine in order to improve the combustion process consists, among others, of:

– electric control of the fuel injection sequence:
– high pressures and high injection speeds;
– multiphase fuel injection per one power cycle of the engine.

To measure the parameters of the injection and combustion process in engines, it is necessary to use a computer-aided system diagnostic that allow for the recording fast-changing parameters, such as:

– fuel pressure course in the fuel injection process
– pressure of the mixture in the combustion chamber (indicator diagram);
– injector needle lift (duration);
– all of them at the angle of the engine crankshaft rotation throughout its operating range (CR) for one cycle [8].

A favorable solution in the area of the computer-aided development in the engine operation process was the joint decision of car companies regarding the widespread placement of a standardized diagnostic socket in vehicles. This connector DLC - Data Link Connector enables the connection between an external scanner - EOBD (European On Board Diagnostics) / OBD (On Board Diagnostics) and the vehicle on-board information system. The detailed structure of this connector is given in SAE J 1962 and ISO 15031-3 documentation. A detailed description of the diagnostic connector pinout is included in one of the bibliography items [6].
As far as vehicle servicing is concerned, we deal with an integrated diagnostic system of the Common Rail fuel supply system with the EOBD system [11].

2. COMPRESSION - IGNITION ENGINE WITH COMMON RAIL INJECTION SYSTEM AS A REGULATION OBJECT

The Common Rail fuel injection system is designed for CI diesel engines with direct injection. It enables greater flexibility of adjusting the fuel injection system in comparison to previous engine fuel systems.

A higher injection pressure (up to approx. 260 MPa), a variable fuel injection start, fuel injection in divided doses (up to nine doses per one injection), as well as fuel injection pressure adjusted to the engine load, result in higher engine efficiency and lower emissions of limited exhaust components.

It was achieved thanks to the use of piezoelectric injectors. The method of fuel spray and injecting it into a divided dose has a fundamental impact on the parameters of the injection and combustion process. It reduces the content of NO_x nitrogen oxides in the exhaust gases, and is also characterized by a lower degree of engine noise due to the lower values of the pressure increase in the combustion chamber per one degree of crankshaft rotation.

Motor fuels simulate the development of compression-ignition (CI) engines. We are still dealing with increasingly stringent restrictions on the limited exhaust gas components and the noise level which forces the continuous development of engine design and fuel properties. New EURO VI emission standards determine the permissible levels of: nitrogen oxides (NO_x), hydrocarbons (C_nH_m), carbon monoxide (CO) and solid particles (PM).

Earlier systems of powering CI engines did not keep up with the performance of these tasks in high-speed engines. It refers to the power supply systems for CI engines equipped with in-line injection pumps, distributor injection pumps as well as pump injectors with spring injectors.

In the diagnostics of parameters concerning these design solutions, the were used fuel pressure courses in the fuel injection process as the function of the rotational angle of the crankshaft.

It was necessary to optimize the control parameters (input and output) while using the latest achievements in electrical control systems. It was necessary to adapt the diagnostic parameters of the engine, separately for each cylinder, not only for the first cylinder of the engine, as it used to be. The latest system of powering CI engines equipped with the Common Rail fuel supply system is trying to meet these requirements.

The parameters of the fuel injection process significantly determine the combustion process in the engine cylinder and, consequently, they are decisive as far as the engine power is concerned.

Each internal combustion engine, including CI engine, is a complex control object so mechanical-hydraulic and pneumatic control systems which have been used so far, could not cope with the optimization of control parameters in terms of their tasks [15]. The essence of such an engine is to meet the requirements for environmental protection standards by optimizing the correlation between input or output parameters (or their characteristics) thanks to the use of an integrated, electronic control system. These parameters are controlled in a closed feedback loop, e.g. between fuel and air and exhaust fumes composition. This whole system of regulation and control must result in obtaining the assumed torque characteristics of the engine as a function of rotational speed.

3. DIAGNOSTICS TESTS OF INJECTION AND COMBUSTION PARAMETERS

The diagnostic parameters of the injection and combustion process were tested on a single-cylinder AVL 5402 research engine.

The view of the test stand is shown in Fig. 1.

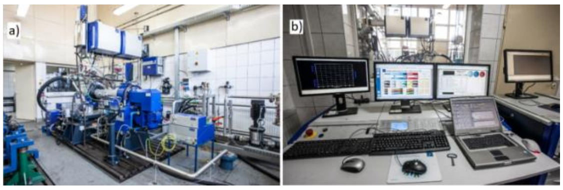


Fig. 1. AVL test bed: (a) general view of the test bed, (b) view of the control room

For the detailed analysis of the phenomenon of self-ignition delay, a compression-ignition engine was selected: a single-cylinder engine from the company AVL LIST GES.M.B.H. Vetrieb RGW – Länder in Graz, Austria. It is prof. Hans List's research center and it is of world renown. It carries out research and construction works for new engines on behalf of car companies.

This AVL 5402 engine is equipped with a Common Rail fuel supply system and an electronically controlled injector. It has a two-phase fuel injection system with a pilot dose of fuel. The basic technical parameters of the AVL 5402 engine are given in Table 1.

Table 1. Engine characteristics

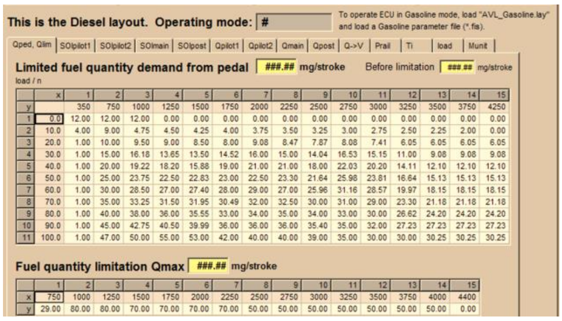
Number of cylinders	1
Bore	85.01mm
Stroke	90.00mm
Displacement	511.00cm^3
Combustion type	Compression ignition
Valve system	4 valves
Compression ratio	17.0 ÷ 17.5
Fuelling system	Common Rail
Maximum effective power, without supercharging	6 kW
Maximum effective power, with supercharging	16 kW
Rated engine speed	4200 min^{-1}
Maximum injection pressure	180 MPa

The measurement processes and the viewing of engine operating parameters and their edition are possible thanks to computers equipped with PUMA Open v 1.5.3 and AVL INDICOM v2.4 software. PUMA Open v 1.5.3 from AVL is used for automation and enables the creation of new tests. PUMA Open software can be used for HIL simulations.

To use AVL PUMA Open software, Microsoft Windows 7 or XP operating system with TEN ASYS IN time and Oracle database is required whereas the INDICOM v 2.4 program is used to handle the parameters of the combustion process.

The basic functions of the fuel injection system include fuel injection control, mainly an injection start, injection pressure and a fuel dose. Their main task is to maintain high efficiency of the engine and a high repeatability of the injection pressure, which ensures engine smoothness. The parameters of the injection and combustion process in an engine equipped with the Common Rail system are controlled by the controller which limits their voltage to the permissible range. The controller is responsible for the pressure and dose of the injected fuel for each engine load as well as for the correct injection start angle. An exemplary view of the engine control map is shown in Fig. 2. In this case, the coordinates were: the AVL 5402 engine speed and a dose for the desired engine load in the range from 0 - 100%.

Extensive studies regarding the use of the load map in the AVL 5402 engine with the use of dual fuel supply was also conducted. Detailed test results are included in the [16, 17] publications.



	x	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
y		350	750	1000	1250	1500	1750	2000	2250	2500	2750	3000	3250	3500	3750	4250
1	0.0	12.00	12.00	12.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	10.0	4.00	9.00	4.75	4.50	4.25	4.00	3.75	3.50	3.25	3.00	2.75	2.50	2.25	2.00	0.00
3	20.0	1.00	10.00	9.50	9.00	8.50	8.00	9.08	8.47	7.87	8.08	7.41	6.05	6.05	6.05	6.05
4	30.0	1.00	15.00	16.18	13.65	13.50	14.52	16.00	15.00	14.04	16.53	15.15	11.00	9.08	9.08	9.08
5	40.0	1.00	20.00	19.22	18.20	15.88	19.00	21.00	21.00	18.00	22.03	20.20	14.11	12.10	12.10	12.10
6	50.0	1.00	25.00	23.75	22.50	22.83	23.00	22.50	23.30	21.64	25.98	23.81	16.64	15.13	15.13	15.13
7	60.0	1.00	30.00	28.50	27.00	27.40	28.00	29.00	27.00	25.96	31.16	28.57	19.97	18.15	18.15	18.15
8	70.0	1.00	35.00	33.25	31.50	31.95	30.49	32.00	32.50	30.00	31.00	29.00	23.30	21.18	21.18	21.18
9	80.0	1.00	40.00	38.00	36.00	35.55	33.00	34.00	35.00	34.00	33.00	30.00	26.62	24.20	24.20	24.20
10	90.0	1.00	45.00	42.75	40.50	39.99	36.00	36.00	36.00	35.40	35.00	32.00	27.23	27.23	27.23	27.23
11	100.0	1.00	47.00	50.00	55.00	53.00	42.00	40.00	40.00	39.00	35.00	30.00	30.00	30.25	30.25	30.25

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
x	750	1000	1250	1500	1750	2000	2250	2500	2750	3000	3250	3500	3750	4000	4400
y	29.00	80.00	80.00	70.00	70.00	70.00	70.00	50.00	50.00	50.00	50.00	50.00	50.00	50.00	0.00

Fig. 2. Limited fuel quantity [mg/stroke]

In research on a new design of internal combustion engines or their modernization in design plants, the following diagnostic parameters of the combustion process are measured:

– indicator diagram;
– self-ignition delay angle;
– combustion pressure angle in the function of the rotation angle of the crankshaft (including Pc_{max});
– angle of combustion start;
– combustion process duration agle as well as using appropriate software such as:
– the degree of the increase in combustion pressure (engine hardness);
– the degree burning 50% of the fuel dose;
– the degree of burning 90% to 100% of the fuel dose.

The detailed definitions of the parameters of the engine injection and combustion process along with their graphic page can be found in the bibliography item.

The Fig. 3 shows the injection start angle or rather the start of activating the electric impulse to open the injector.

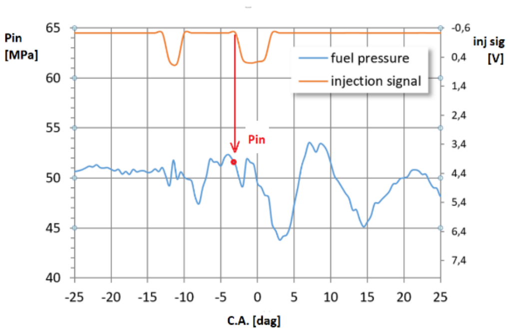


Fig. 3. Exemplary course of the fuel pressure before the injector was used in the AVL5402 P_{in} = f [deg] engine with P_{in} determination method

The prototype DI20c engine was used to optimize injection pressures and the design of the engine timing system in order to improve the thermal performance of the engine and to reduce smoke emissions.

Extensive research in this field with the use of diagnostic programs was conducted under the supervision of the International Association of Information and Engineering Technologies in 2020 [18].

The KH-RT fuel decay model and the advanced ECFM-3Z combustion model from the Kiado Academy in Budapest, Hungary in 2019 were used to conduct 3D simulations regarding the air-fuel mixture formation and the combustion process.

A numerical simulation with a modified KIVA III V2 model, with the use of an optical engine to test the fuel atomization angle for the characteristics of the combustion process is also used [3].

In research on optimization of injection and combustion processes in engines, diagnostic experimental numerical models were also used to describe the ignition processes in the combustion chamber of the engine [18].

In the operating conditions of engines, however, their technical condition is assessed on the basis of operational inspection procedures or the need to diagnose current malfunctions. The fuel supply system of CI diesel engines with conventional injection systems and the Common Rail system is characterized by a large number of technical defects - mainly injectors and injection pumps.

An exemplary diagnostics of the power supply system of the VW Caddy III 2.OTDI engine is shown on the stand in the service station where VCDS software and the diagnostic system were used (Fig. 4).

The tested parameters of differences in averaged fuel doses, injected into individual cylinders, are shown in Fig. 5.

It should be mentioned here that the uniqueness of fuel doses injected into the engine cylinders causes the uniqueness of the aforementioned parameters of the combustion process. They can be defined as indicators of the uniqueness (variability) of a given parameter from the formula:

$$X(P_{c\max}) = \frac{\sigma(P_{c\max})}{(\overline{P}_{c\max})} = \frac{\sqrt{\frac{1}{k-1}\sum_{i=1}^{k}\left[(P_{c\max})_i\right] - \left(\overline{P}_{c\max}\right)^2}}{\overline{P}_{c\max}}$$

where:

σ(*Pcmax*) – standard deviation;

i (*Pcmax*) – maximum pressure in the combustion chamber;

(Pc_{max}) i – maximum pressure in the combustion chamber in this cycle;

k – numer of analized cycles.

Fig. 4. Diagnostics of the power supply system in the conditions of a service station

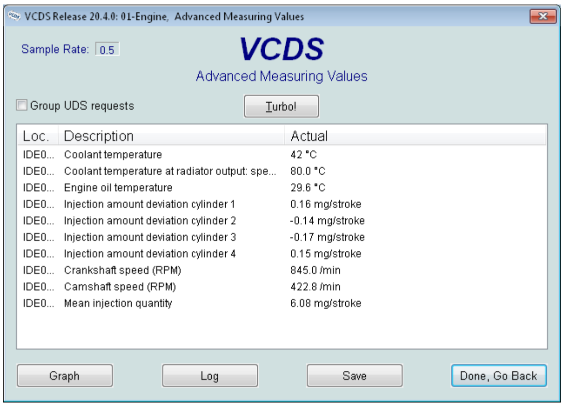


Fig. 5. Diagnostics of the injection equipment with Common Rail system of the VW Caddy III 2.0TDI 74 KM 2015 vehicle, capacity 1968 cm^3

Due to the uniqueness of the injection and combustion process parameters, we deal with the variability of the engine torque during its operation. It mainly concerns the operation of the engine in transient conditions. Under steady-state operating conditions, the torque varies within a certain range during one revolution of the crankshaft. Consequently, the angular velocity of the engine crankshaft is not constant. Consequently, the movement of the engine crankshaft is characterized by an irregular running of the engine. To improve it, a flywheel is mounted at the end of the crankshaft.

In order to reduce operating costs of the engine, the components of the Common Rail fuel supply system, in particular injection pumps and injectors, are subject to damage verification on diagnostic test stands.

For this purpose, there are diagnostic testers and computer-aided diagnostic stations with appropriate programs in order to restore their parameters in accordance with a manufacturer's recommendations. These processes are performed after replacing damaged parts and carrying out adjustments.

The Hartidge CRI Expert diagnostic test stand for testing CR injectors in compression-ignition engines is shown in Fig. 6.

Fig. 6. Hartidge Sarbe CRI Expert test stand for testing injectors in compression-ignition engines with the display of test results

Examples of the test results of the Continental A2C injector from this test stand are included in the test card - Fig. 7.

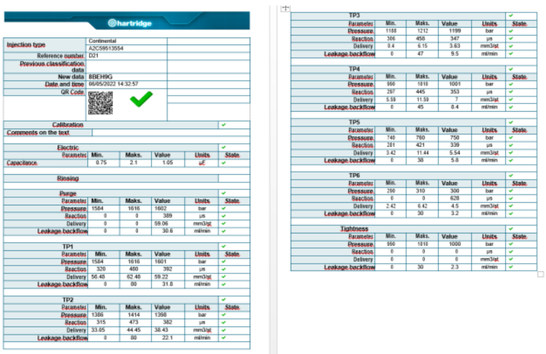


Fig. 7. Exemplary diagnostic test results Continental A2C59513554 injector

Tests of injection pumps are performed on diagnostic test tables where there is a possibility to check the uniformity of dosing of individual injection pump sections, and the speed characteristics of the injection pump can be prepared on the basis of the results of fuel doses. Computerization of the stand enables to obtain a research card. The view of the BOSCH EPS 708 test bench is shown in Fig. 8, and the exemplary results of the tests of the Mercedes Sprinter CDI injection pump can be seen in Fig. 9.

Fig. 8. BOSCH EPS 708 test bench for diagnostics of injection pumps including the visualization of test results

Fig. 9. Exemplary results of diagnostic test of the injection pump dosage characteristics for Mercedes Sprinter CDI

The latest designs of BOSCH test tables are controlled by computers for diagnostics with proper software and are equipped with 23 different additional tool sets so that injection pumps from all manufacturers can be diagnosed on them [22]. Obtaining certain values, e.g. ΔP (overpressure in the combustion chamber as a difference between the injection pressure and the pressure in the combustion chamber), using appropriate programs, enables to calculate a number of parameters in the field of creating a combustible mixture (Fig. 10).

They can include the mentioned below diagnostic parameters:
- initial velocities of the fuel atomization stream injected into the combustion chamber of the engine;
- critical speed of fuel decay;
- critical value of the diameter of fuel droplets;
- fuel stream microstructure;
- vertical angle of the injected fuel.

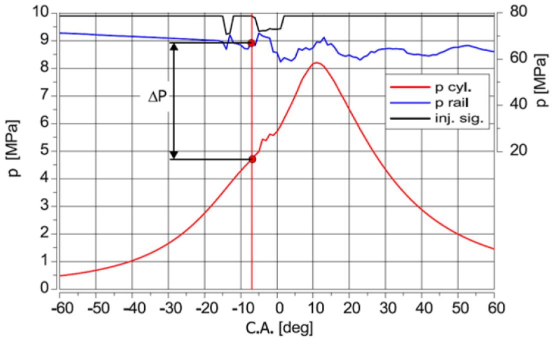


Fig. 10. Maximum overpressure definition before starting the injector in the combustion chamber

Extensive research material in this field on the AVL5402 engine for various mixtures of diesel oil with methyl ester of rapeseed oil fatty acids RME is included in the author's publication.

Below, there are the parameters of the fuel injection process that can be read directly from the monitors of testing devices or diagnostic kits equipped with computer systems with appropriate software. The following diagnostic parameters can be included:

– start of the fuel injection angle;
– end of the fuel injection angle;
– injection duration;
– maximum injection pressure.

CONCLUSIONS

This publication presents the most important research areas of diagnostic parameters regarding compression-ignition engines, with particular emphasis on engines with the Common Rail fuel supply system.

Increasingly stricter barriers concerning exhaust gas emission limits imposed by environmental protection force manufacturers of motor fuels to modify the existing ones.

As mentioned in the publication, these diagnostic studies are carried out in four main areas. Most attention is devoted to new designs of engine fuel supply systems. The latest solution is the Common Rail fuel supply system. The entirety of these tests also concerns the engine diagnostics during the process of its operation as well as the repair of damaged components in order to place them in service again.

The problem has been discussed thoroughly, in the publication, particularly paying attention to the participation in the computer processes with high computing power, in order to simulate and optimize the diagnostic parameters of the injection and combustion process in an engine with the Common Rail fuel supply system. Due to the high cost of tests on engine test benches, model tests of these processes, with professional software for diagnostics are also used.

Declaration of competing interest: The author declares no conflict of interest.

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Prof. dr hab. inż. **Wincenty LOTKO** – represents a scientific discipline mechanical engineering.
He is an author of over 230 publications. He carnies research concerning diagnostics of internal combustion engines and the application of alternative fuels in diesel engines