ISSN: 1231-4005
e-ISSN: 2354-0133
DOI: 10.5604/01.3001.0012.2481

STUDY ON FUEL INJECTOR WITH HYDRAULIC AMPLIFIER (HADI) ON THE EXAMPLE OF MERCEDES-BENZ ACTROS VEHICLE WITH OM 471.9 ENGINE

Łukasz Mórawski

Motor Transport Institute, Diagnostics and Servicing Process Department
Jagiellonska Street 80, 03-301 Warsaw, Poland
tel. +48 22 4385147
e-mail: lukasz.morawski@its.waw.pl

Grzegorz Trawiński

Military University of Technology, Faculty of Mechanical Engineering
Institute of Motor Vehicles and Transportation
Gen. Witolda Urbanowicza Street 2, 00-908 Warsaw, Poland
tel. +48 261 837046, fax: +48 261 837366
e-mail: grzegorz.trawinski@wat.edu.pl

Abstract

One of the recent trends in heavy-duty engines has been the introduction of common rail injector with hydraulic amplifier (HADI – Hydraulically Amplified Diesel Injector) capable of considerable fuel pressure injection increase in reference to fuel pressure prevailing in rail of common rail fuel system. An example of a solution of this type of injectors is the two-valve CRIN4 injectors manufactured by Bosch. They allow the control of the fuel flow rate during injection process and therefore have an impact on the combustion process. In this article, advantages related to their use are described, which allow the engines with such injectors to meet the limits of the admissible content of toxic compounds in the exhaust gases defined in the EURO VI standard. An experimental study of the operation of the Bosch IV generation common rail system was performed on the Mercedes-Benz Actros. During measurement engine load, engine speed, waveforms (electric currents) controlling operation of the selected injectors, fuel pressure in the rail and the control current of high pressure pump control valve (metering unit) were registered. Interpretations of recorded waveforms were made, indicating the areas of application of the various modes operation. The use of CRIN4 injectors for the rapid reduction of fuel pressure in rail was observed, which supports the metering unit (ZME) for pressure control.

Keywords: *diesel engines, common rail systems, fuel injectors, injection rate modulation, boot injection*

1. Introduction

Ecological aspects motive the continuous development of internal combustion engines. Despite the introduction of hybrid powertrains and electric motors into the powertrain systems, CI engines will continue to be the basic type of truck drive in the next few years [1, 4,].

The introduction of the EURO VI standard has forced the widespread replacement of unit injector systems by common rail fuel systems in heavy-duty vehicles. This was due to the fact that unit injector systems were not able to provide limits of toxic compounds stated by EURO VI emission standard.

Common application of common rail systems in the internal combustion engines of heavy duty vehicles (DAF, Renault, Volvo, Iveco, Mercedes-Benz) was conditioned by their merits-the ability to regulate the number of injections per cycle (injected-fuel quantity), the time interval between the injection same cycle and injection pressure depending on crankshaft rotational speed and engine load. In addition, special fuel injection control algorithms allow for high injection precision regardless of wear (within specified limits) of the system components [7]. Adjustment off operating parameters of the fuel supply system has a major influence not only on the emission, but by controlling the emission of individual components of the exhaust gases optimizes the operation of the exhaust gas aftertreatment systems. In commercial vehicles, mainly they include a combination of EGR system, DOC catalytic converter, DPF filter, and SCR system.

Continuous development of common rail systems, irrespective of manufacturer, have higher and higher injection pressure, which range from a maximum of 130-140 MPa in the firsts generations, up to 250-270 MPa for the newest. This is because in general the increase in fuel injection pressure improves the combustion process.

Until recently, the only parameter of the CR system that could not be changed was the injection rate shaping by means of variable nozzle or pressure modulation (omitting Digital Rate Shaping). An example of systems with such capability is 4th generation common rail made by Bosch with CRIN4 HADI injectors (HADI − *Hydraulically Amplified Diesel Injector*) [5, 6]. In terms of construction and properties, HADI injectors differ significantly from conventional CR injectors. Increasing the injection pressure in the HADI injector relative to the fuel pressure in the rail, increases the fuel flow rate coming out of nozzle, lowers the load on the high-pressure pump (torque needed for its drive) and reduces the possibility of leakage [2, 3].

2. Construction and operation of CRIN4 (HADI) injectors

The CRIN4 injector is shown in Figure 1.

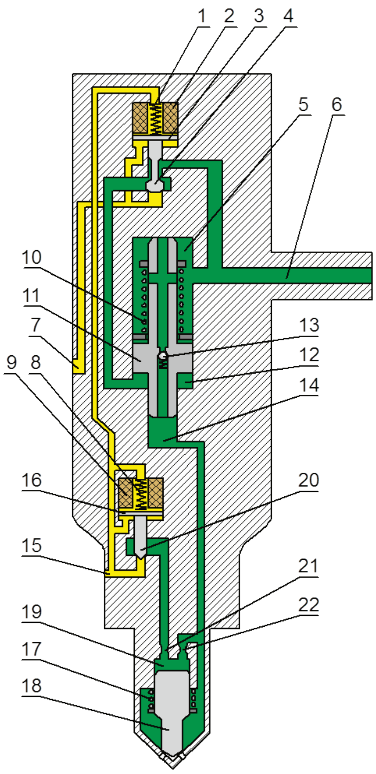

Fig. 1. CRIN4 (HADI) injector

1 – amplifier valve spring; 2 – amplifier solenoid coil; 3 – amplifier valve armature; 4 – amplifier valve stem 5 – chamber above amplifier piston; 6 – fuel supply; 7 – amplifier drain; 8 – nozzle valve spring; 9 – nozzle solenoid coil 10 – amplifier spring; 11 – amplifier piston; 12 – chamber under amplifier piston; 13 – non-return valve 14 – increased fuel pressure chamber; 15 – nozzle drain; 16 – nozzle valve armature; 17 – needle spring 18 – needle; 19 – control chamber; 20 – nozzle valve stem; 21 – drain orifice; 22 – inlet orifice

The CRIN4 injector consists of two basic modules: the amplifier module (top of the injector) and the nozzle module (bottom part). Unlike conventional injectors, there are two control valves – the amplifier valve and the nozzle valve. If the amplifier coil is not powered by the current, the injector acts just like the classic injectors (with one control coil) used in earlier generations of CR systems.

The fuel is supplied from the rail to the injector through fuel supply *6*, through which the non-return valve *13* flows into the control chamber *19* and through the amplifier valve to the chamber beneath amplifier piston *12* If the solenoid coil *9* is not energized, the resulting fuel pressure in the chamber and the spring *17* presses the needle *18* into the nozzle seat. The injector is closed. At the same time, the lack of power supply to the amplifier solenoid coil *2* causes that the fuel pressure in chamber *5* and *12* is the same, equal to the fuel pressure in the fuel rail.

Fuel injection under fuel pressure from rail (without its increase in the injector) is performed when the nozzle valve is energized, without energizing amplifier valve. As a result of nozzle valve opening, the fuel flows out through drain orifice *21* from the control chamber to the nozzle drain *15*. As a result of difference in diameter of drain and inlet orifice *22* (drain orifice diameter is larger), the fuel pressure in the control chamber drops (as in the classical injector) and the needle is lifted. Fuel is injected in to the combustion chamber.

In order to increase the fuel pressure in the nozzle, it is necessary to energize amplifier solenoid coil *2*. In this case, the coil attracts the three-way valve armature *3* together with stem *4*. In result, the stem cuts off the fuel supply to the chamber beneath the amplifier piston *12*. The connection of the chamber *12* with amplifier drain *7* allows evacuating fuel. Because the upper surface of the amplifier piston is much larger than the lower part, the fuel pressure from the rail acting on the larger upper surface of the piston (in chamber *5*) begins to compress the fuel contained in the chamber *14* (smaller surface area). As a result, the fuel pressure increases about *2* times in the nozzle. The amplification effect is terminated by cutting off power supply to the amplifier coil – fuel pressure in chamber *12* and *5* is balanced. Amplifier piston spring and the fuel pressure in chamber *12* are lifting the amplifier piston upwards (to the position shown in Figure 1). The use of two independently controlled valves (modules) allows modulating injection pressure, thus allowing to injection rate shaping. To archive this, moment in which the amplifier valve is activated has to be varied according to moment in which nozzle valve is activated.

In case of energizing amplifier valve before nozzle valve, a *square* injection (classical injection for CR systems) is achieved, with a fuel injection pressure boost as compared to the fuel pressure in rail (Figure 2a).

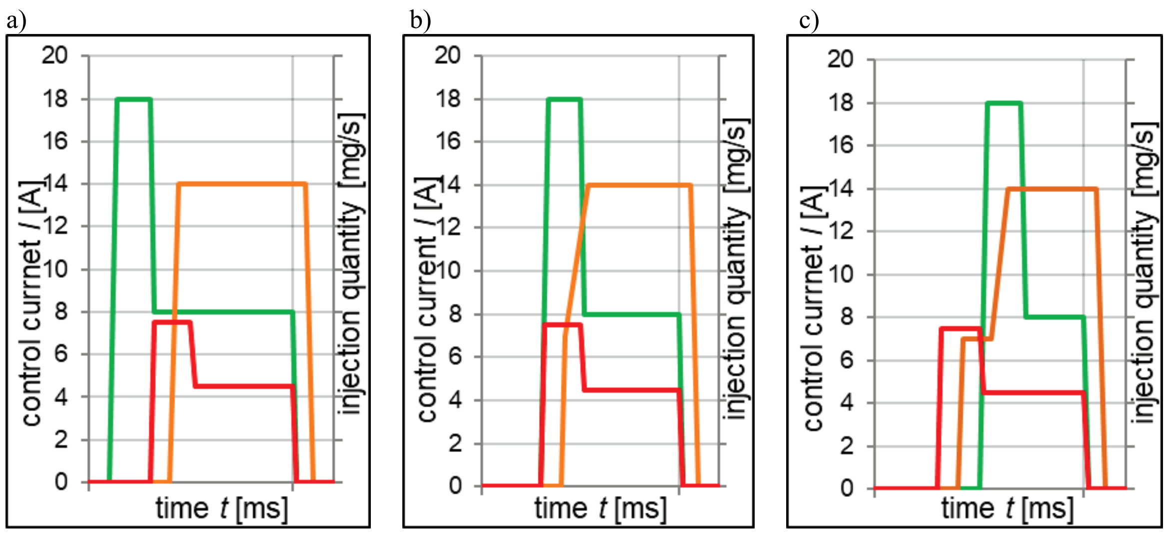

Fig. 2. Current curves for triggering nozzle valve (red), amplifier valve (green) and injection rate (orange) for square type injection (a), ramp (b) and boot (c)

Energizing at the same time both coils, pressure modulation result in *ramp* type injection. In the initial phase, the injection flow rate is determined by the fuel pressure value in the rail. A further, slower increase in fuel flow rate intensity is induced by the amplifier. The timing of both valves can be selected so that the start of the pressure boost occurs after reaching the maximum injection pressure defined by pressure in rail (Figure 2b).

If the amplifier valve is activated later than the nozzle valve, *boot* type injection is applied. The maximum injection flow rate from rail at first is retained for some time. After this time, amplifier is activated and injection flow rate is increased (Figure 2c). For each type of injection described, the supply of the coils of both valves ends at the same time.

Available scientific and technical literature generally describes the general construction of HADI injectors, but does not provide precise information on how they operate in different engine operating conditions. Experimental research has been carried out in this area.

3. Program and research methodology

Experimental research was conducted to demonstrate how HADI fuel injectors were controlled using the injectors in the Mercedes-Benz Actros 1842 engine. The 6-cylinder OM 471.9 engine with 12.8 dm^3 displacement uses Bosch CRIN4-25 common rail with a maximum fuel injection pressure of 250 MPa.

The following were recorded:

- torque and crankshaft rotational speed,
- control signals for two CRIN4 injectors; for each injector, the current for the amplifier solenoid coil and the nozzle solenoid coil, currents were recorded using the current clamps with a current measurement range of up to 20 A with voltage output,
- voltage signal from the fuel pressure sensor.

The operating conditions of the engine were determined on the basis of the information obtained from the engine ECU using a diagnostic tester connected to the vehicle's On-Board Diagnostic system. Due to the short time of injectors operation and high frequency of operation, two oscilloscope cards were used, whose work was synchronized. Conversion of the U_{out} voltage signal from the pressure sensor to the p_{rail} fuel pressure in the rail was based on the sensor characteristic $p_{rail} = f(U_{out})$. The diagram of the measuring system is shown in Figure 3.

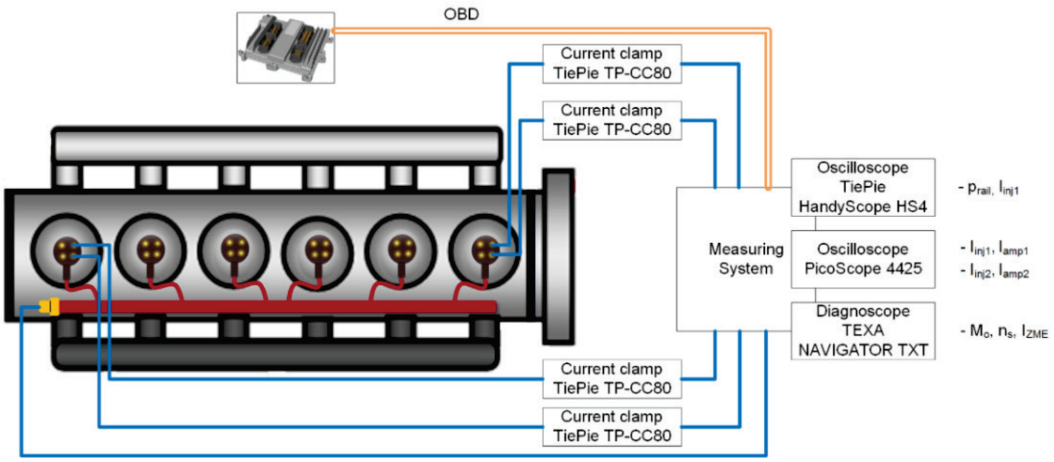

Fig. 3. Measuring system for acquisition control signals and fuel pressure signal of CRSN4 common rail with CRIN4 injectors applied in OM 471.9 engine

Measurements were made for three different engine-operating conditions:

- no load-vehicle immobilized,
- at the load caused by driving track itself,
- at the load caused by vehicle combination-track with trailer and loading.

In all cases, the measurements were made in quasi-steady driving conditions of the examined truck (constant vehicle traveling speed, registration time-10 seconds). For every engine operating condition, it was also attempted to force a controlled reduction of the fuel pressure in the rail caused by injectors' amplifiers.

Sample of the recorded signals are shown in Fig. 4.

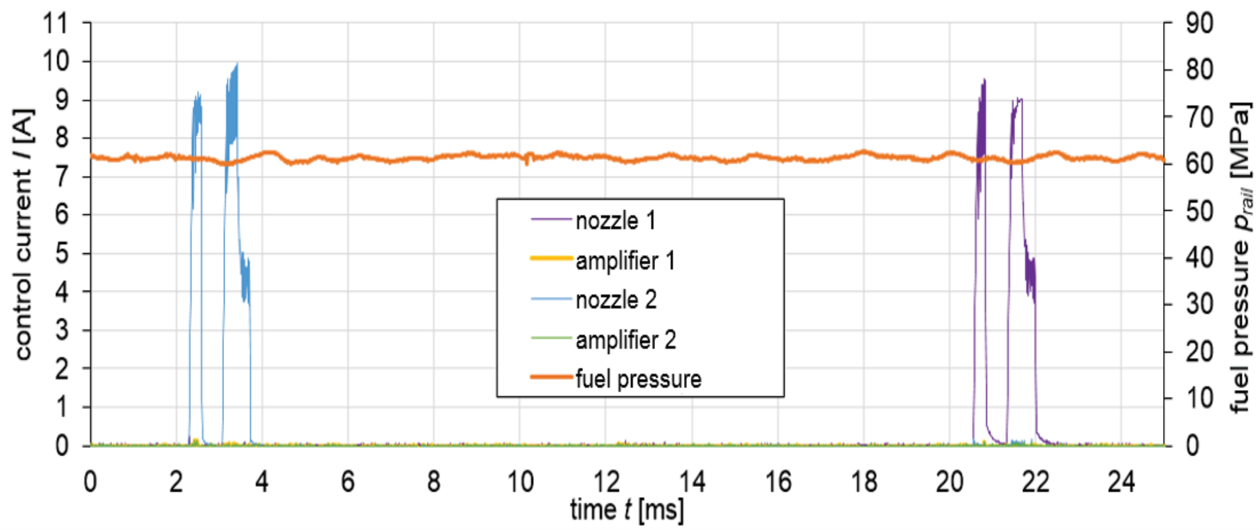

Fig. 4. Control current curves of CRIN4 injector for nozzle and amplifier valves and fuel pressure in the rail

Points (determined by engine speed and torque) for which measurements were made are shown in Fig. 5. Crosses indicate the points for which fuel injection was with activated amplifier (see Fig. 2c).

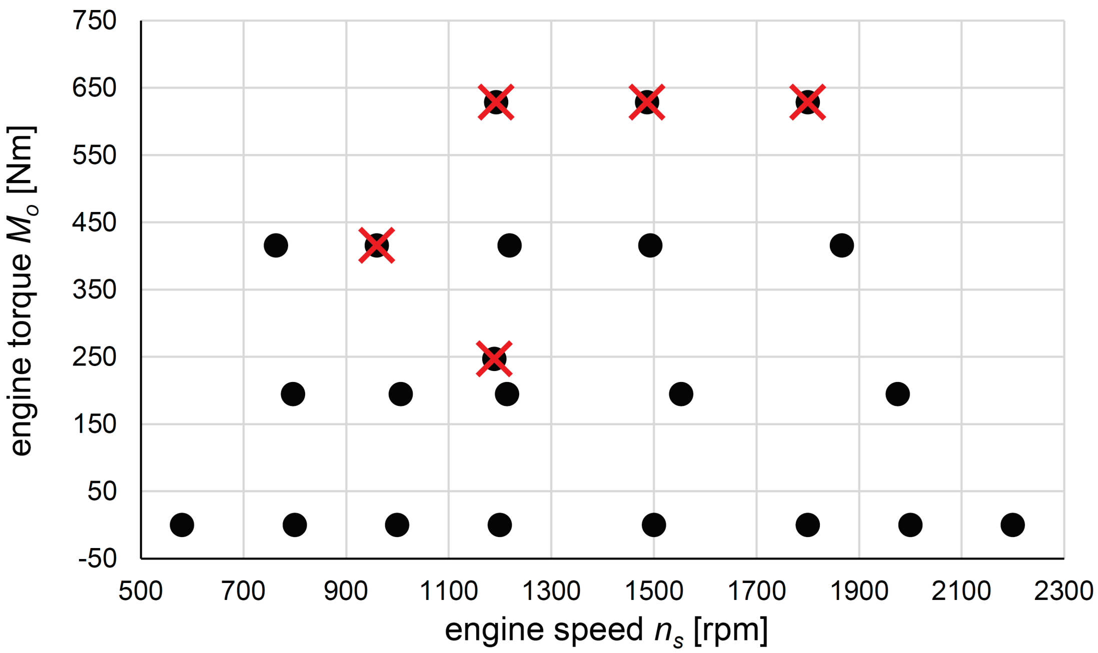

Fig. 5. Measuring points determined by engine speed and torque

Based on the collected data, it has been found that there is a great relationship between the main injection time and the injection pressure. The increase in rotational speed results in a shortening of the fuel injection time and a simultaneous increase in fuel pressure in the rail.

Examples of recorded signals for injector performing *square* fuel injection (Fig. 2a) are shown in Fig. 6.

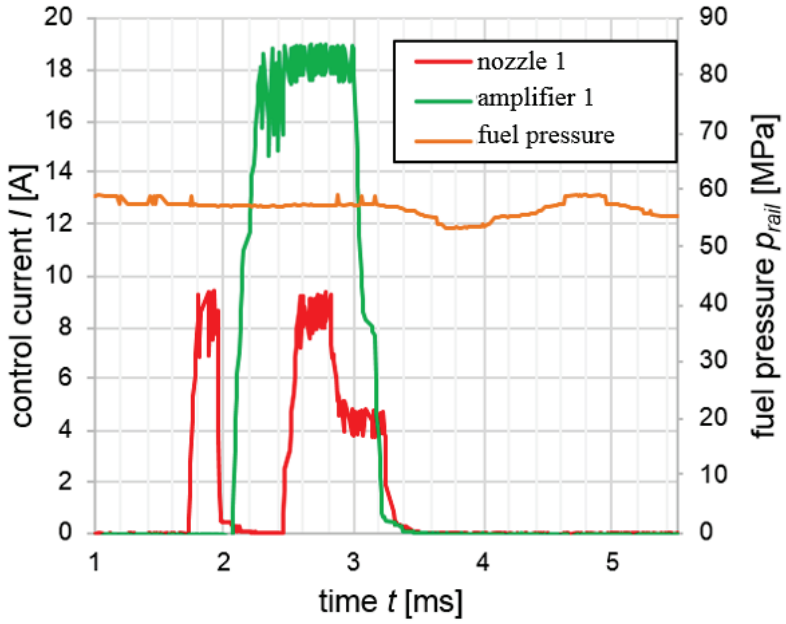

Fig. 6. Control current curve for square type injection and fuel pressure for n_s = 1200 rpm, M_o = 250 Nm

The conventional square type fuel injection, under these conditions is characterized by an earlier (0.41 ms average) activation of the amplifier valve compared to the nozzle valve under main injection. The amplifier valve is also switched off earlier (0.08 ms average). In the pre-injection phase, the amplifier valve was left unenergized and the nozzle was supplied with fuel pressure from the rail. The amplitudes of the fuel pressure fluctuations in rail resulting from the actuation of both valves reached a maximum value of up to 5.4 MPa.

Boot type injection was achieved when performing measurements under vehicle combination load (Fig. 7). This injection is characterized by the activation of the amplifier valve on average 0.1 ms after activation of the nozzle valve. For this operating mode, no pre-injection has been observed. Role of pre-injections is taken over by the first phase of main injection (with reduced flow rate).

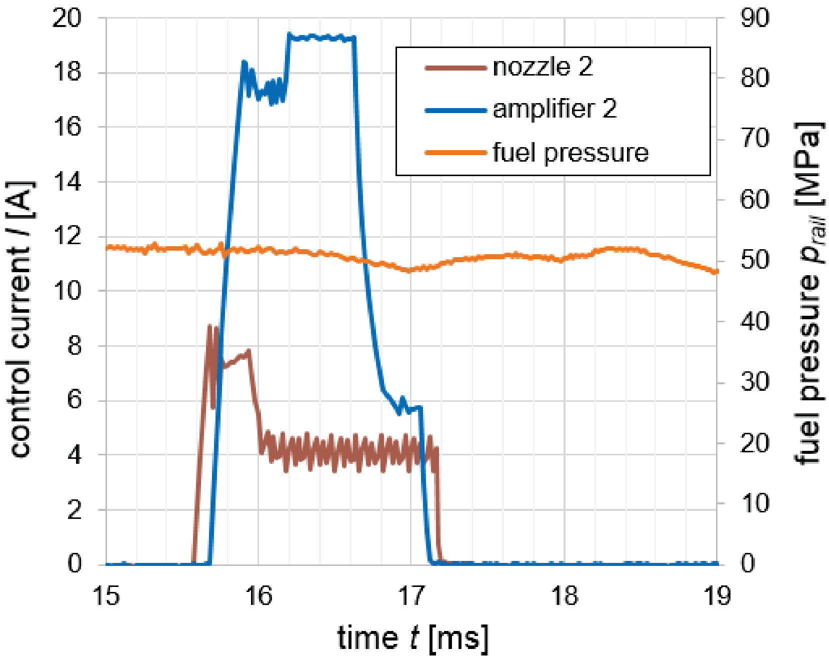

Fig. 7. Control current curve for boot type injection and fuel pressure for n_s = 1000 rpm, M_o = 420 Nm

On the basis of the gathered data, the fuel injection strategy realized by HADI injectors can be roughly determined. The increase in fuel pressure in rail (most noticeable when changing torque at constant speed) occurs regardless of whether the fuel injection is with or without amplifier activation. This means that when changing fuel injection without amplification on injection with amplification, the fuel injection pressure must rise dramatically (more than twice). With a small change in rail pressure and injection quantity, this forces to reduce proportionally injection time. The opposite situation, in which the injection pressure would change gently, is practically impossible to achieve due to the need rapidly to reduce the pressure in the rail. This would probably require a pressure control valve on the rail, which would result in a significant reduction in the hydraulic efficiency of the system.

During measurements performed without load, attempts were made to reduce fuel pressure in the rail using injectors' amplifiers. It is realized by releasing fuel from the chamber under the amplifier piston to the drain circuit. Sample illustrations of the relationship found along with parameters describing this process are shown in Fig. 8.

It has been found that before the engine ECU activates, the amplifier modules, there is a time t_s in which the fuel injection does not occur. Only after the fall of the rotational speed below the specified limit, the amplifier modules of the individual injectors are activated. The effect is lowering the fuel pressure in the rail. For a long time t_s (even in the order of seconds), there was a noticeable drop in fuel pressure due to system leaks. Values of parameters describing the process of controlled fuel pressure drop in rail are given in Tab. 1 (before depressurisation with amplifiers) and in Tab. 2 (during fuel pressure lowering). The p_{ss} parameter describes the rate of fuel pressure drop in the rail determined by the research results.

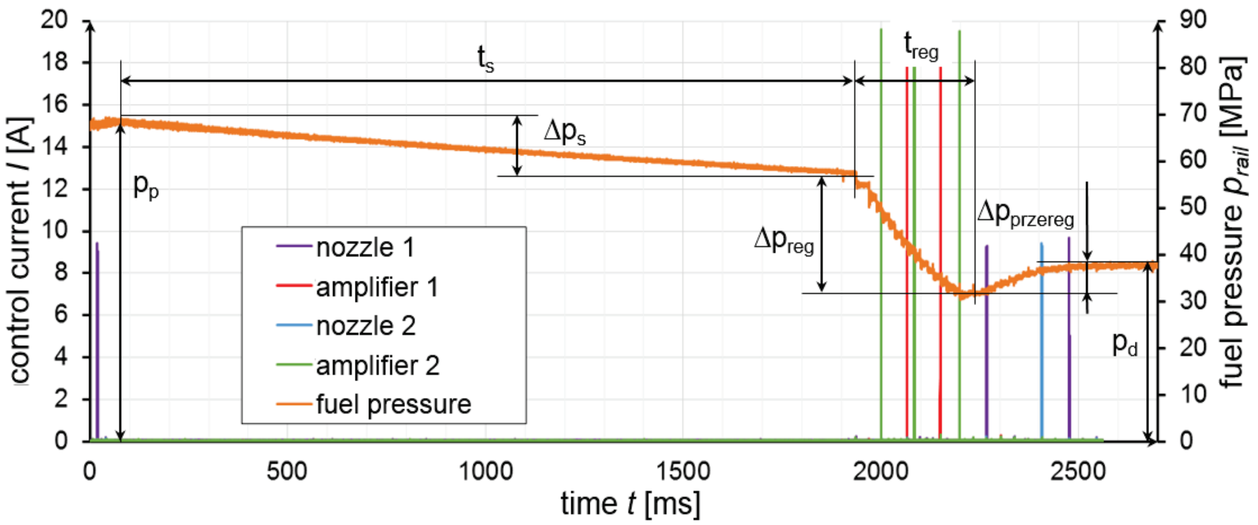

Fig. 8. Control current curves and fuel pressure during fuel pressure reduction performed by amplifiers n_s = 1800 rpm; M_o = 0 Nm

t_s – time of pressure drop caused by system leakage; t_{reg} – time of pressure regulation by amplifiers; p_p – initial pressure; p_d – target pressure; Δp_s – pressure drop caused by system leakage; Δp_{reg} – pressure drop during regulation $\Delta p_{przereg}$ – overshoot, disparity between target pressure and the lowest pressure value during regulation

It has also been observed that the sequence of the amplifier modules activation causes a regular reduction of the fuel pressure in the fuel rail during the t_{reg} time by value Δp_{reg}. This is shown in Fig. 8. The time of the fuel pressure adjustment t_{reg} compared to the time of the pressure drop caused by system leaks t_s is considerably shorter and ranges from 160 to 300 ms depending on the engine speed. For engine under load, they are shorter. For example, at torque of 195 Nm pressure was reduced by amplifiers from 172 ms (for 1000 rpm) to 121 ms (2000 rpm).

Tab. 1. Parameters values before pressure regulation – engine torque M_o = 0 Nm

n_s [rpm]	t_s [ms]	p_p [MPa]	Δp_s [MPa]	Δp_{ss} [MPa/s]
800	-	50.5	-	-
1000	453	59.8	2.4	5.4
1200	1048	64.1	4.9	4.7
1500	1263	63.6	6.3	5.0
1800	1882	67.4	10.4	5.5
2000	1190	65.7	7.7	6.4
2200	1506	63.5	8.9	5.9

Approximate values of most parameters were obtained when driving a track at different engine speeds and constant torque, while the average fuel pressure drop Δp_j caused by single amplifier activation was 1.5 MPa under these conditions (Fig. 9).

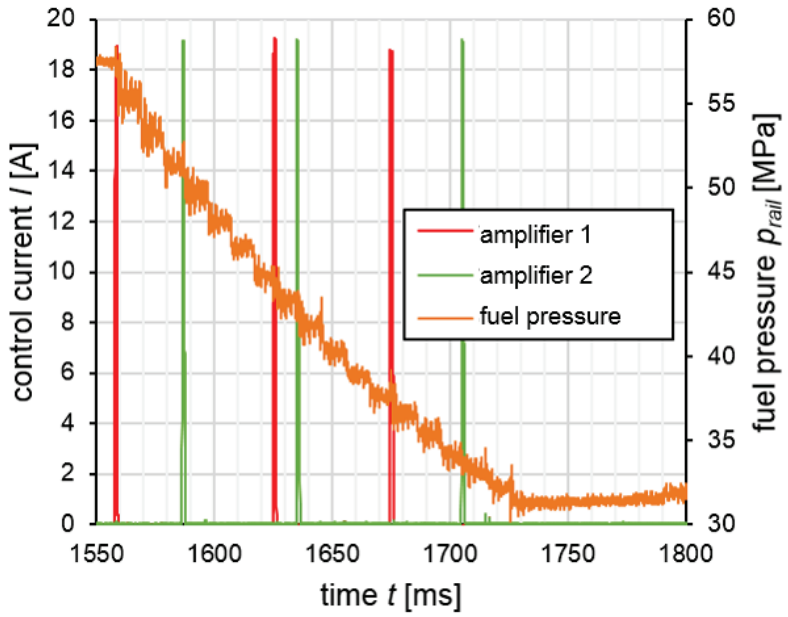

Fig. 9. Fuel pressure regulation caused by amplifier valves triggering, n_s = 2200 rpm, M_o = 0 Nm

Tab. 2. Parameters values during pressure regulation – engine torque M_o = 0 Nm

n_s [rpm]	t_{reg} [ms]	Δp_{reg} [MPa]	Δp_j [MPa]	number of activation	$\Delta p_{przereg}$ [MPa]
800	164	19.5	1.4	14	7.1
1000	242	26.7	1.5	18	6.5
1200	300	27.5	1.7	16	5.5
1500	220	24.0	1.5	16	4.4
1800	263	26.0	1.6	16	6.2
2000	160	26.2	1.5	18	5.8
2200	170	26.3	1.5	18	6.0

For certain measurement conditions, the nozzle valve activation has also been registered in the process of amplifiers fuel pressure regulation. Their timings position relative to the amplifier signals differs from the typical, registered during operation of the engine in quasi-stable operating conditions. With only one nozzle valve energizing, the signal duration is typically 0.250 ms. It occurs at the end of the amplifier valve signal (Fig. 10a). When there are two signals (Fig. 10b), the second nozzle valve activation (with a duration of 0.250 ms) is activated as in the case of a single signal, while the first (0.270-0.410 ms) occurs at the beginning of the amplifier signal.

The given time values correspond to the time required to complete the pre-injection. It can be assumed that single signals are used to determine the minimum opening time of a nozzle using the method of recording the momentary speed change. If the control signal has opened the nozzle, the fuel injection and the torque are generated. This increases the instantaneous speed of the crankshaft. The signal time is shortened until the instantaneous speed does not increase and minimum opening time is set.

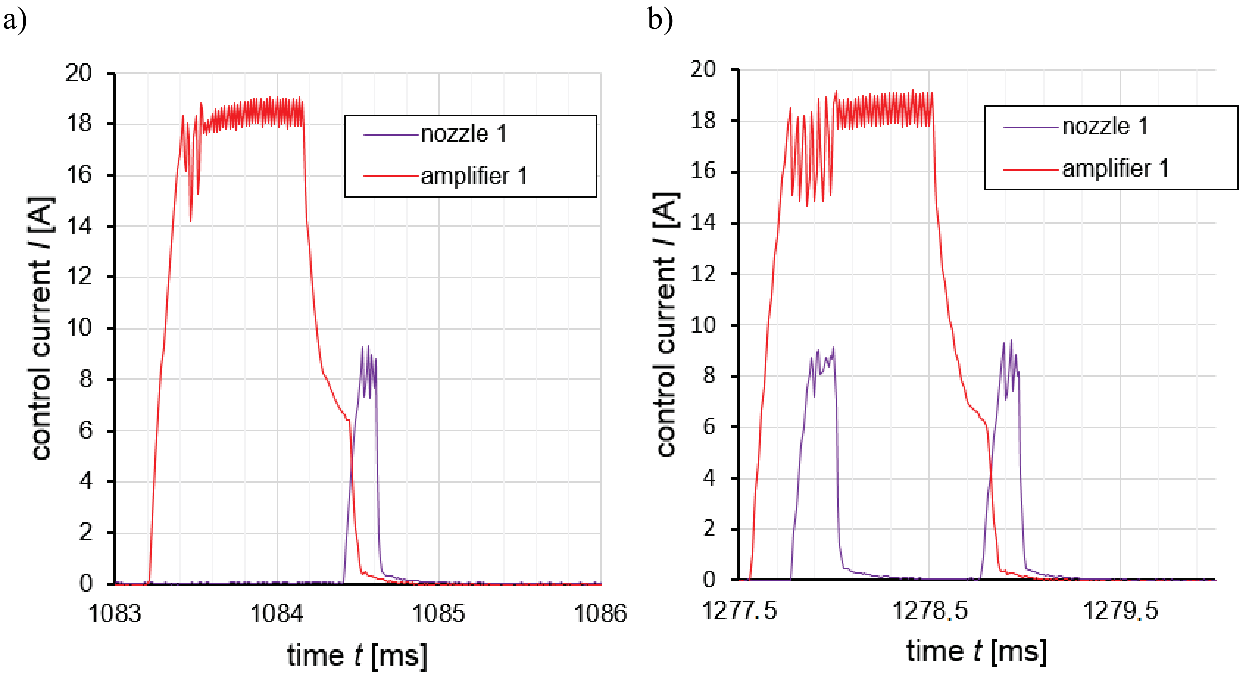

Fig. 10. Short nozzle valve activation during fuel pressure regulation by amplifiers, n_s = 1200 rpm

The nozzle signals were often registered at an increased idle speed (no load) at the first cycle of the amplifier modules activation during fuel pressure regulation. They never came out for all the amplifier signals. Sometimes, they occurred at the end of the fuel pressure adjustment period using amplifier modules.

4. Conclusions

1. The CRIN4 injectors provide three characteristic types of fuel injection. Obtained results did not allow to uniquely determining the torque and engine speed limit below which fuel injection without the amplification is present, and above which fuel injection with fuel pressure boosting starts. The tests show that, for the OM 417.9, this limit is between 420 Nm and 629 Nm, but it is not known at what engine speed range. Square injection is carried out in nearly all engine speed range with low engine load. Boot injection is registered at low engine speeds, in conditions where there is a low level of exhaust gas recirculation.
2. Studies have shown that for OM 417.9 engine, CRIN4 injectors also act as fuel pressure regulators for the rail, when the engine breaking is performed to reduce fuel pressure by more than 20 MPa. Under these conditions, when the fuel injection does not occur, only the amplifier valve is activated, which enables the pressure drop in the rail by releasing fuel through the injector to the drain circuit. CRIN4 injectors cannot be used accurately to regulate fuel pressure (such as pressure control valves) due to introduction of significant pressure pulsations in the fuel rail. It is important to determine whether the activation of the amplifiers modules takes place according to the phases of the engine's operation or whether they are independent at this time, which require further testing combined with the additional registration of the angular position of crankshaft.

3. Fuel injections (control signals for nozzle valves) recorded when CRIN4 fuel injectors act as pressure regulators point to other tasks than generating torque-are likely to be used to determine the minimum injector opening time for single activation or act as post-injections for efficient exhaust gas aftertreatment.
4. The registered control signals (current) for the nozzle and amplifiers valves of the OM 417.9 engine injectors differ from the values reported in the literature. For the nozzle valve, this is a value greater than 1.2 A in the pickup phase and 0.3 A lower for the holding phase. For the amplifier valve, the maximum current in the pickup phase is 0.5 A lower, while for the holding phase is 2.4 A lower.

References

[1] Baumgarten, C., *Mixture Formation in Internal Combustion Engines*, Spinger-Verlag Berlin Heidelberg, Germany 2006.
[2] Bennett, S., *Medium/Heavy Duty Truck Engines, Fuel & Computerized Management Systems*, Delmar Cengage Learning, USA 2012.
[3] Desantes, J. M., Benajes, J., Molina, S., González, C.A., *The modification of the fuel injection rate in heavy-duty diesel engines. Part 1: Effects on engine performance and emissions*, In Applied Thermal Engineering, Volume 24, Issues 17-18, pp. 2701-2714, 2004.
[4] Jankowski, A., Kowalski, M., Environmental Pollution Caused by a Direct Injection Engine, Journal of KONES, Vol. 22, Issue 4, DOI: 10.5604/12314005.1168461, pp. 133-138, 2015.
[5] Jankowski, A., Sandel, A., *Influence of Fuel Quality on Mixture Preparation and Exhaust Emissions from Diesel Engines with Common Rail System,* Journal of KONES. Internal Combustion Engines, Vol. 10, Issue. 3-4, 2003.
[6] Seebode, J., *Dieselmotorische Einsptitzratenformung unter dem Einfluss von Druckmodulation und Nadelsitzdrosselung*, PhD thesis, Institute of Technical Combustion, University of Hanover, Germany 2004.
[7] Tanabe, K., Kohketsu, S., Mori, K., Kawai, K., *Innovative Injection Rate Control with Next Generation Common Rail Fuel Injection System*, FISITA World Automotive Congress, Seoul, Korea 2000.

Manuscript received 12 September 2017; approved for printing 11 January 2018