INFLUENCE OF HIGH INJECTION PRESSURE ON FUEL INJECTION PERFOMANCES AND DIESEL ENGINE WORCKING PROCESS

by

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In Moscow Automobile and Road Construction University, investigations are carried out in the field of Diesel engine working process perfection for complying with prospective ecological standards such as Euro-6 and Tier-4. The article describes the results of the first stage of experimental research of the influence of injection pressure up to 3000 bar on working processes of Diesel engine and its fuel system. Justification of the design of a common rail injector for fuel injection under 3000 bar pressure is presented. The influence of raising injection pressure (up to 3000 bar) on the fuel spray propagation dynamics is demonstrated. The combined influence of injection pressure (up to 3000 bar) and air boost pressure on fuel spray propagation dynamics is shown, including on engine emission and noise.

Key words: *common rail fuel injection system, high pressure injection, common rail injector, pollution, Diesel, noise*

Introduction

Development of modern engines is aimed at the fulfillment of strict pollution standards at the same time preserving or improving such qualities as: fuel efficiency, power, noise level, *etc*.

In Moscow Automobile and Road Construction University (MADI), application studies and experimental research are carried out (unique identifier RFMEFI58015X0002) with financial support of the state represented by the Ministry of Education and Science of the Russian Federation by the agreement No 14.580.21.0002 on granting subsidies aimed at the development of accumulator type (common rail) diesel fuel supply systems with controlled injection characteristics for transport Diesel engines complying with prospective ecological standards on emission of pollutant substances with exhaust gases such as Euro-6 and Tier-4.

In a number of articles [1, 2], published by foreign researchers and leading manufacturers of fuel equipment, it is affirmed that one of the efficient ways of solving this task is the increase of injection pressure up to 3000 bar, exhaust gas re-circulation ratio to 50% and air boost pressure to 5 bar. The results of choice of electro-hydraulic common rail injector for vehicle Diesel engine operating at injection pressure from 2000 to 3000 bar were presented and the effect of increasing injection pressure on Diesel engine parameters were shown.

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The purposes of the research are:

- to select of the main technical solutions of electro-hydraulic injector Diesel engine of a vehicle with injection pressures of 2000 bar and more, and
- assessment of possibilities of improving the working process of a Diesel engine by increasing the injection pressure more than 2000 bar.

Experimental set-up

For carrying out experimental research of common rail injection systems, experimental set-up was developed in MADI. Experimental set-up includes an engine bench and test stand for fuel systems.

The last one is used for supplying fuel into a combustion chamber of a Diesel engine being investigated during its testing.

The stand has modular design which makes it possible to its adaptation for current research tasks and various designs of fuel systems.

The stand consists of:

- electric drive of high pressure pump shaft with smooth control of rotation frequency up to 3000 rpm,
- reinforced fuel rail with high pressure sensor (measurement range 0-4000 bar with a possibility of a short overload up to 6000 bar) and indicating pressure gauge (measurement range 0-6000 bar), and
- system of fuel spray visualization into clear and vented chamber with possibility to create pressurization inside it.

The control system developed for the fuel system testing stand makes it possible to carry out tests of fuel systems either on engine or separately and fulfills the following functions:

- maintaining the required pressure in the fuel rail p_{rail} via feedback connection with the pressure sensor, and
- control of a common rail nozzle (CRN) with electromagnetic or piezo valve drive, and
- fulfilling fuel injection in compliance with the predetermined position of the crankshaft (injection advance angle $\varphi_{\mathrm{in.adv}}$).

The fuel sprays registration system mounted on the stand features a transparent ventilated chamber with the possibility of creating an excess pressure inside. The spray registration is made with a high speed digital camera in a light passing through the spray.

The main parameters of the Diesel engine are indicated in tab. 1. The cross-section of the combustion chamber is presented in fig. 1.

Table 1. Parameters of experimental one cylinder engine

Cylinder diameter, D [mm]	120
Piston stroke, S [mm]	130
Cylinder displacement, V_h [l]	1.47
Compression ration, ε	15.4:1
Number of valves	2 intake, 2 exhaust
Injector location	Central
Cooling system	Water type
Combustion chamber type	Gesselman

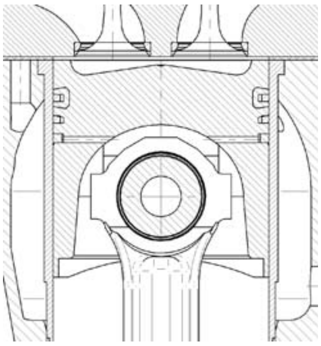

Figure 1. Cross-section of combustion chamber of experimental one cylinder engine

Charging air pressure in the intake system was created by a rotary type compressor with electric drive. A back pressure was created in the exhaust manifold by a controlled throttle valve for imitation of a turbine operation.

Emissions of NO_x, CO, and HC were registered by the Infralight 11P gas analyzer. For measuring exhaust smoke opacity C, the Infralight 11D smoke analyzer was used which was determining the light flow weakening. Manufacturer of smoke analyzer is OOO NPP ECO-INTECH (Russian Federation).

Indicating of the Diesel engine working process was carried out using the AVL measurement complex (Indimeter 619 with pressure sensor GU21D).

The structural noise of the Diesel engine examined was measured by the hardware and software complex LMS Pimento and microphone PCB Piezotronics.

A modified rail of common rail type fuel system with electronic control was used as an injection system.

The influence of raising injection pressure on flow characteristic of CRN

For research was chosen CRN with the following design features:

- CRN No. 1 with a solenoid control valve unloaded from fuel pressure forces,
- CRN No. 2 with a solenoid control valve loaded with fuel pressure forces (number of bores: 7, diameter of bores: 0.13 mm),
- CRN No. 3 with piezoelectric drive of the control valve (number of bores: 7, diameter of bores: 0.13 mm), and
- CRN No. 4 with a solenoid control valve unloaded from fuel pressure forces and integrated reservoir.

The main parameters of the nozzles are indicated in tab. 2.

Table 2. Parameters of nozzles

Injector	Number of nozzle bores	Diameter of nozzle bores [mm]
1	7	0.105
2	7	0.12
3	7	0.13
4	8	0.09

The evaluation criteria in favor of technical solutions have been appointed:

- maintaining of working capacity of injection pressures in the range of 2000-3000 bar,
- cycle-by-cycle injection stability, and
- no skipping or delaying injection at the injection pressure of 2000-3000 bar.

Work of injectors was estimated under the definition of flow characteristic and dependence of the injection rate on the control impulse and fuel pressure. Injection rate determined by weighing a quantity of fuel collected during the check number of cycles.

Figure 2 shows the flow characteristic of CRN No. 1. At pressures above p_{rail} = 1600-1800 bar its work became unstable with skipping and delaying of injection. The reason for these effects may be friction in valve assembly, increasing under high pressure.

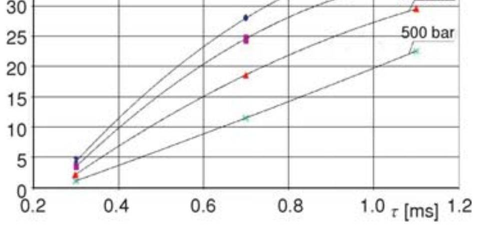

Figure 2. Dependence of the injection rate *Q* on the control impulse τ and fuel p_{rail} of CRN No. 1

The further increase of p_{rail} over 2400-2600 bar becomes impossible due to a brush increase of the drain flow. Supposedly it is caused by the seal failure in the valve due to its deformation.

The CRN No. 2 was more resistant than CRN No. 1 under pressure more than 2000 bar (fig. 3) because cycle-by-cycle injection stability of CRN No. 2 is not disturbed.

The results obtained by injecting of fuel into the air without counter pressure are the base for future analysis of the influence of pressure in the Diesel engine cylinder on fuel injection jet with pressure over 2000 bar were presented in fig. 4.

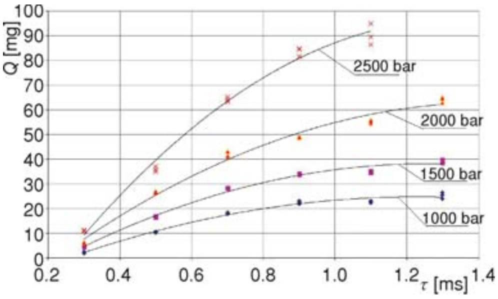

Figure 3. Dependence of the injection rate Q on the control impulse τ and fuel p_{rail} of CRN No. 2

Photos presented in fig. 4 were obtained when the injectors were opened by equal control impulse with duration $\tau = 0.7$ ms. Photoregistration was made with a high speed video camera having frequency 5000 Hz.

At p_{rail} 500 bar, the cone angle of the spray core is 3-6° fig. 4(a) and corresponds with the results obtained earlier in MADI, 3-5° [3]. When raising injection pressure, the cone angle of the spray core increases. In this way, at 1000 bar, spray core angle is 4-9°, at 1500 bar 7-9°, and at 2000 bar and 2500 bar – 9-10°, fig. 4(c).

Raising of p_{rail} has led to decrease of the angle of the spray boundary layer. At 500 bar, the boundary layer cone angle is 22-27° fig. 4(b), at 1000 bar it is 20-28°, at 1500 bar 18-20°, at 2000 bar 18-19°, and at 2500 bar 17-18° fig. 4(c).

The decrease of oscillations of the spray boundary layer relating to its axis was demonstrated. The largest oscillations were registered at $p_{\text{rail}} = 500$ bar, fig. 4(a), they could be approximately estimated within 10°. Further, with the increase of p_{rail}, the core oscillations decreased and became practically imperceptible at 2500 bar, fig. 4(c).

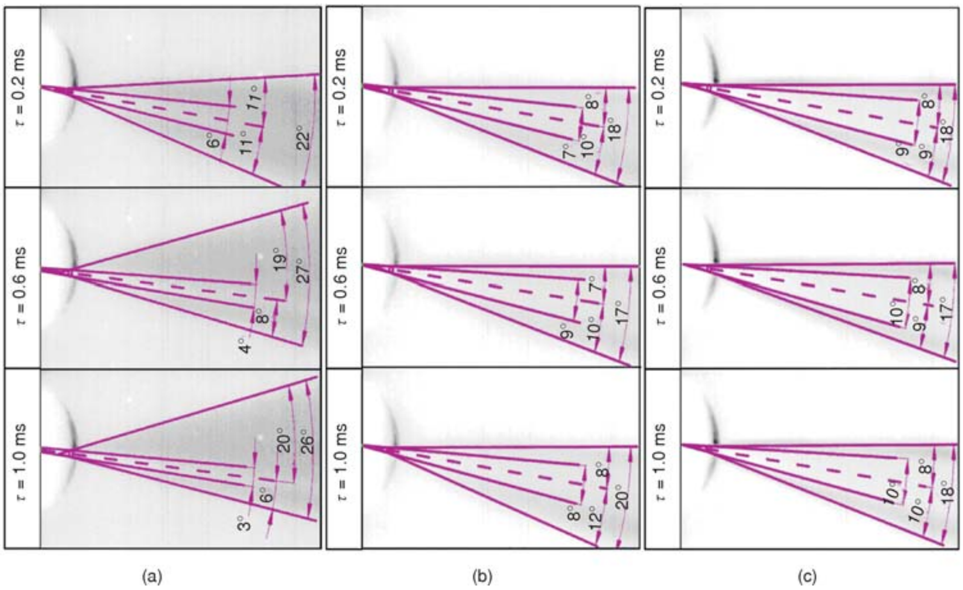

Figure 4. Photos of the spray of CRN No. 2 at different p_{rail}; (a) $p_{\text{rail}} = 500$ bar, (b) $p_{\text{rail}} = 1500$ bar, and (c) $p_{\text{rail}} = 2500$ bar, τ – time from the instant of injection start

In spite of stable operation of CRN No. 2 at p_{rail} = 2000 bar, further increasing the pressure in the fuel ramp caused deviations from the normal operation of the injectors:

– at pressure p_{rail} = 2500 bar and higher, the CRN demonstrated the increase of drain fuel flow,
– the increased fuel flow causes a strong heating of fuel, the nozzle itself and high pressure pump. The body temperature in the control valve area in which the fuel throttling takes place attains 130 °C, and
– nozzle operation becomes unstable (a low intercycle stability) and a high power for high pressure pump drive is required (more than 7.5 kW).

One of the reasons of these negative effects is the fact that fuel pressure creates an axial load on the valve in direction reverse to the spring pressing the valve to its seat. At p_{rail} = = 2500 bar and higher, the spring force becomes insufficient for overcoming the pressure, hence hydraulic insulation of the closed valve fails, as well as the process of its seating.

The CRN No. 3 was more resistant to pressure increase than versions No. 1 and No. 2. This nozzle operated at excess fuel pressure 10 bar in the drain line. Dependence of its injection rate *vs.* control impulse duration and fuel pressure is presented in fig. 5.

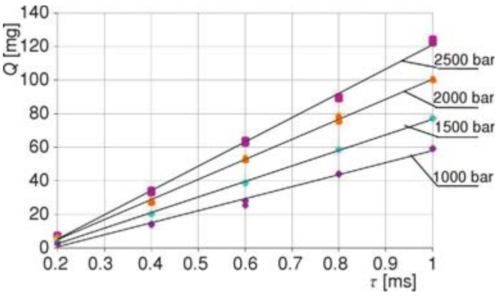

Figure 5. Dependence of the injection rate Q on the control impulse τ and fuel p_{rail} of CRN No. 3

In the process of the injector testing at pressure higher than p_{rail} = 2500 bar, for activation of the CRN, currents and voltages were required which values were considerably higher than those used in modern fuel systems (charging a piezo element with 60 A current at constant 220 V).

The control valve of this injector is not unloaded from fuel pressure force but in contrast to the previous version, this force increases the reliability of closing the valve. To open the valve pressed by the high pressure, one has to increase the piezo drive force, that is, increase the values of currents and voltages.

At pressure higher than p_{rail} = 2500 bar, the minimal interval between injections is 200 ms. This is caused by the increase of pressure in the hydro-plunger chamber which results in leakages of fuel from its volume. The pressure increase in the chamber is caused due to the increase of the force transferred by it to the valve loaded with fuel pressure. For restoring good operation condition of the injector, a considerable time needed for filling the chamber volume is required.

At a pressure of over 2500 bar activation of the injector with an interval between the control pulses less than 200 ms leads to a complete termination of fuel injection. The reason of it is the loss of working capacity of the hydraulic valve actuator.

On pressure range 1000-3000 bar compromising of working process of CRN No. 4 was not observed. Drive of the injector CRN No. 4 was more fast acting then CRN No. 3. Therefore CRN No. 4 was chosen for the research on engine. Its dependence of the injection rate on the control impulse and fuel pressure in the fuel rail is shown in fig. 6.

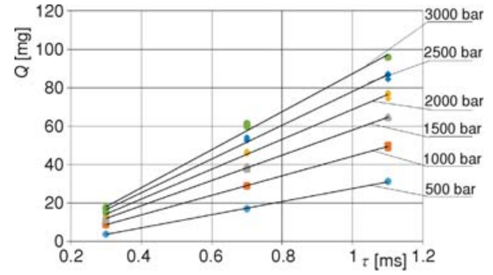

Figure 6. Dependence of the injection rate Q on the control impulse τ and fuel p_{rail} of CRN No. 4

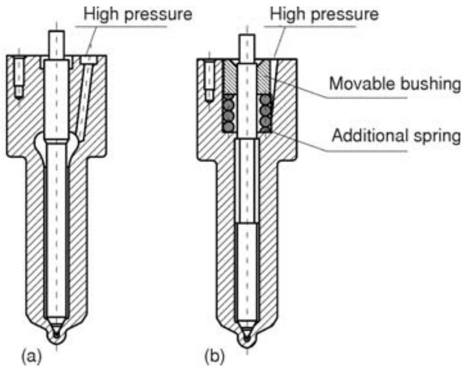

Figure 7. Design variants of nozzles of common rail injectors: (a) without movable bushing (b) with movable bushing

The design of the nozzles of CRN No. 3 and CRN No. 4 differs by the use of a *movable bushing*.

Conducted computational studies have shown that the nozzles without movable bushing fig. 7(a) using steel 18H2N4MA provide a valid factor of safety at a pressure up to 1600 bar. The further increase of pressure results in cracking the area of a lateral fuel channel one input to the nozzle pocket two and deterioration of the nozzle body. Computational studies carried by finite elements method using SolidWorks system.

Transfer to the design of a nozzle with a movable bushing without lateral channel fig. 7(b) makes it possible to increase the pressure 1.56 times (to 2500 bar). At the same time, it becomes possible to decrease the diameter of the needle sealing surface. Decrease of the needle diameter with the same design of the nozzle assembly makes it possible to decrease the return spring pressing force and decrease the impact force of the needle at the instant of its seating which also promotes the increase of the nozzle service life.

Computer simulation carried out in MADI demonstrated that the use of more durable steels for example grade H18K8M5T enables to raise the injection pressure to 3000 bar while preserving the same service life.

Analysis of the results and the calculated and experimental data allowed us to make a choice of basic technical solutions of electro-hydraulic diesel injectors operating at injection pressures of 2000 bar or more:

- solenoid control valve, unloaded from the forces of pressure of fuel,
- built-in into injector body fuel volume (injector with increased internal volume), and
- nozzles with movable bushing.

The influence of injection pressure on working parameters of Diesel engine

Assessment of the quality of the working process is carried out by using parameters of engines efficiency and pollution.

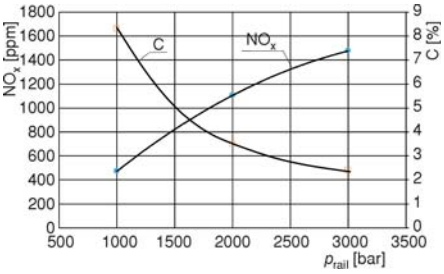

Figure 8. Dependence of content of NO$_x$ and soot C in Diesel engine exhaust gases on the p_{rail} (n = 1500 rpm, p_e = 5.1 bar, $\varphi_{in.adv}$ = 10 °CA to TDC)

At the first stage of engine tests, ecological effect of increasing the injection pressure value was estimated, at that, a single injection without turbocharging and exhaust gas re-circulation was used.

The tests were carried out at different pressures p_{rail} and constant values of torque T_e = = 60 Nm (p_e = 5.1 bar) and engine speed n = = 1500 rpm.

The results obtained at injection advance angle $\varphi_{in.adv}$ = 10 °CA to TDC are shown in fig. 8.

The increase of p_{rail} from 1000 to 3000 bar did not have any considerable impact on emission of HC and resulted in the decrease of exhaust smoke opacity. But NO_x emissions increased due to the growth of the working process severity. It is seen from fig. 9 that to decrease the emissions of NO_x, it is reasonable to decrease the value of $\varphi_{\text{in.adv}}$.

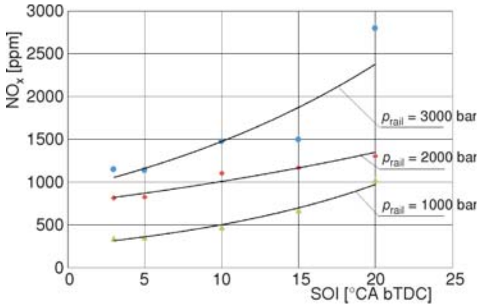

Figure 9. Dependence of NO_x content in exhaust gases on the injection advance angle $\varphi_{\text{in.adv}}$ (n = 1500 rpm, p_e = 5.1 bar)

The decrease of the injection advance angle results in the growth of soot content in the exhaust gases. When the p_{rail} grows up to 3000 bar, these tendencies become more evident.

At the second stage of engine tests, the possibility of improving ecological and economic parameters of the Diesel engine working at pressures p_{rail} up to 3000 bar and higher was analyzed.

Figures 10 and 11 illustrate the positive influence of increasing air boost pressures p_k on NO_x and soot emissions. This is associated with the growth of the charge air temperature in the combustion chamber and growth of the air excess coefficient in case of maintaining the specified value of torque (T_e = 60 Nm, p_e = 5.1 bar) at various combinations of p_{rail} and p_k.

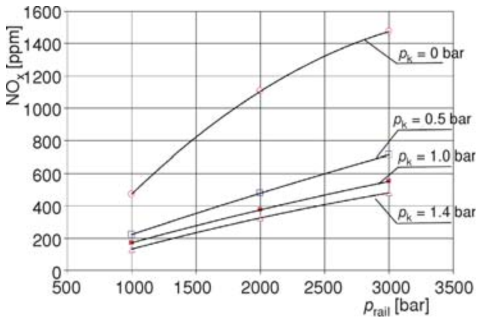

Figure 10. Dependence of NO_x emissions on injection pressure at various air boost pressures (n = 1500 rpm, p_e = 5.1 bar, $\varphi_{\text{in.adv}}$ = 10 °CA to TDC)

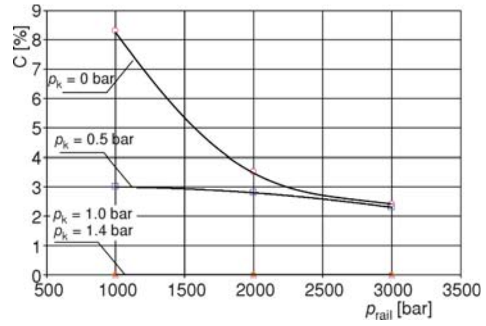

Figure 11. Dependence of exhaust smoke opacity C on injection pressure at various air boost pressures (n = 1500 rpm, p_e = 5.1 bar, $\varphi_{\text{in.adv}}$ = 10°CA to TDC)

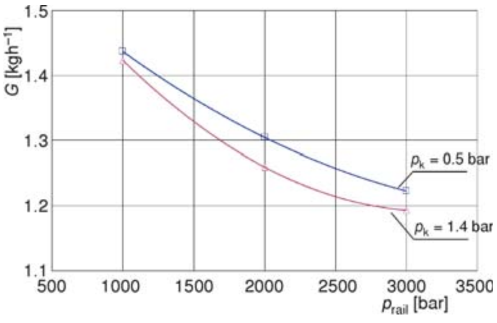

Figure 12. Fuel consumption per hour G_f *vs.* injection pressure at various air boost pressures (n = 1500 rpm, p_e = 5.1 bar, $\varphi_{\text{in.adv}}$ = 10 °CA to TDC)

In this way, at the operation mode n = 1500 rpm, p_e = 5.1 bar, when the pressure p_k grows from 1.0 to 1.4 bar, the exhaust smoke opacity becomes lower the threshold of detection of the smoke analyzer (fig. 11).

This data corresponds to the results of paper [2], in which the fulfillment of the Euro-5 standards is assured in case of combination of p_{rail} = = 3000 bar, p_k = 3 bar and exhaust gases re-circulation ratio ≥ 40%.

Increasing injection pressure and air boost pressure when maintaining the prescribed operation mode (n = 1500 rpm, p_e = 5.1 bar) resulted in reduction of fuel consumption per hour G_f (fig. 12). Thus compared with operation at p_{rail} = = 1000 bar, p_k = 0.5 bar, the value of G_f at p_{rail} = 3000 bar, p_k = 1.4 bar decreased by 17%.

Experimental results obtained correspond to the conclusions of other investigations on the practicability of using fuel systems ensuring injection pressure up to 3000 bar coupled with increasing charging air pressure and exhaust gas re-circulation ratio.

Investigation of the influence of air boost pressures and rail pressure on the level of structural noise of the Diesel engine examined

Measurements were taken at the operation modes of the Diesel engine with the torque 60 Nm (p_e = 5.1 bar) at engine speeds 1000 and 1500 rpm. The pressure values p_{rail} varied from 1000 to 3000 bar and the pressure p_k from 0.5 to 1.45 bar. The results obtained are shown in fig. 13.

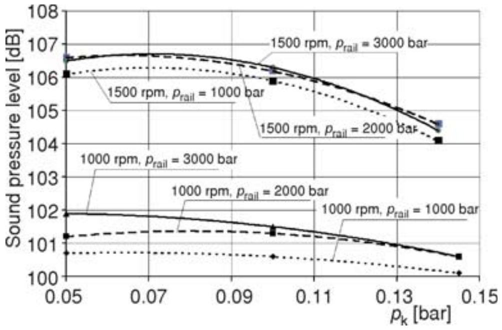

Figure 13. The influence of air boost pressure on structural noise level L_p of the Diesel engine investigated at various engine speeds (p_e = 5.1 bar, $\varphi_{in.adv}$ = 10°CA to TDC)

Raising the pressure p_{rail} results in increasing the noise level (fig. 13) due to increasing the pressure rise speed dp/dφ caused by increasing the quantity of fuel injected during the ignition delay period.

The growth of pressure p_k increases the charge air pressure and temperature in the combustion chamber and thereby decreases the ignition delay period, decreases the value dp/dφ and, as a consequence, the level of structural noise L_p decreases [4].

Raising the engine speed of the Diesel engine investigated from 1000 to 1500 rpm while maintaining the fixed values of p_e = 5.1 bar and injection advance angle $\varphi_{in.adv}$ = 10°CA to TDC augmented the influence of raising the pressure p_k and lowering the pressure p_{rail} on the value of L_p. For example, raising p_k from 0.5 to 1.45 bar at p_{rail} = 3000 bar and n = 1000 rpm caused lowering of L_p by 1.3 dB, while raising p_k from 0.5 to 1.4 bar at p_{rail} = 3000 bar and n = 1500 rpm – by 2.1 db. Variation of p_{rail} from 1000 to 3000 bar at p_k = 1 bar and n = 1000 rpm resulted in increasing L_p by 0.9 dB and at p_k = 1 bar and n = = 1500 rpm – by 0.4 dB.

Higher influence of p_k and lower influence of p_{rail} with raising n can be explained by increasing the speed of air motion in the cylinder of the Diesel engine having a positive impact on mixture formation and increasing the charge air compression speed intensifying its heating and evaporation of fuel.

Conclusions

- Analysis of the results and the calculated and experimental data allowed us to make a choice of basic technical solutions of electro-hydraulic diesel injectors operating at injection pressures of 2000 bar or more:
  - solenoid control valve, unloaded from the forces of pressure of fuel,
  - built-in into injector body fuel volume, and
  - nozzles with movable bushing.

- Increasing the charging air excess pressure p_k lowers considerably emissions of NO_x, which are raising with injection pressure growth. Thus when raising p_k from 0.5 to 1.45 bar at the operating mode of the Diesel engine investigated: $n = 1500$ rpm, $p_e = 5.1$ bar, $p_{rail} = 3000$ bar, and $\varphi_{in.adv} = 10$ °CA to TDC, emissions of NO_x decreased 1.4 times.
- Increasing the injection pressure combined with the growth of charging air pressure is an efficient method of decreasing the exhaust smoke opacity. Thus, at the operation mode $n = 1500$ rpm, $p_e = 5.1$ bar, and $\varphi_{in.adv} = 10$ °CA to TDC, increasing p_k to 1-4 bar results in dropping the exhaust smoke opacity lower the threshold of detection of the smoke analyzer used in the tests.
- Raising the injection pressure results in increasing the level of structural noise due to growing the pressure rise speed. At the operation mode $n = 1500$ rpm, when increasing p_{rail} from 1000 to 3000 bar, the level of structural noise L_p grows by 0.4-0.6 dB depending on the air boost pressure, and at the operation mode $n = 1000$ rpm – by 0.6-1.2 dB correspondingly.

Nomenclature

C – exhaust smoke opacity, [%]
CRN – common rail nozzle
G_f – fuel consumption per hour, [kgh^{-1}]
L_p – sound pressure level, [db]
n – number of revolution
Q – injection rate, [mg]
p_e – brake mean effective pressure, [bar]
p_k – air boost pressure [bar]
p_{rail} – rail pressure, [bar]
TDC – top dead center
T_e – torque, [Nm]

Greek symbols

τ – time of control impulse, [ms]
$\varphi_{in.adv}$ – injection angle, [°CA to TDC]
$dp/d\varphi_{max}$ – maximal values of cylinder pressure rise, [$bar°CA^{-1}$]

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