A CONTROL METHOD OF FUEL DISTRIBUTION BY COMBUSTION CHAMBER ZONES AND ITS DEPENDENCE ON INJECTION CONDITIONS

by

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A method of fuel injection rate shaping of the Diesel engine common rail fuel system with common rail injectors and solenoid control is proposed. The method envisages the impact on control current of impulses applied to the control solenoid valve of the common rail injectors for variation of the injection rate shape. At that, the fuel is supplied via two groups of injection holes. The entering edges of the first group with the coefficient of flow, μ_{cB}, were located in the sack volume and the entering edges of the second group (coefficient of flow, μ_{cH}) – on the locking taper surface of the nozzle body. The coefficients of flow, μ_{cB}, and μ_{cH} differ considerably and depend on the valve needle position. This enables to adjust the injection quantity by injection holes taking into account operating conditions of the Diesel engine and hence – by the combustion chamber zones. Using the constant fuel flow set-up, characteristic of the effective cross-section of the common rail fuel system injector holes was investigated. The diameter of injector holes was 0.12 … 0.135 mm. The excessive pressure at the entering edges varied from 30 to 150 MPa and more and the excessive pressure in the volume behind the output edge – from 0 to 16 MPa.

Key words: *correction injector nozzle, Diesel engine injector nozzle, injector hydraulic characteristics*

Introduction

Tightening of ecological standard results in the requirement for perfection of fuel supply systems of Diesel engines in particular, the most wide spread of them – common rail (CR) fuel systems.

The basic tendencies of development of CR fuel systems – the increase of injection pressure [1-3], ensuring multiple injection with the desired shape of the front edge of the basic injection rate [4-6], and organization of fuel distribution in the combustion chamber [7].

The desired fuel injection law at any operation mode of the engine is formed by variation of the control impulse duration [5, 6, 8-10] and pressure in the CR. It also depends on wave phenomenon originating in the high pressure line and having a considerable impact on the fuel injection process in case of a multistage injection [11].

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The front edge shaping is required for a smooth growth of pressure in the Diesel engine cylinder which insures the decrease of noise and mechanical strength of engine parts, decrease of NO_x emission.

The basic methods of target impact on the injection rate shape are:
- the use of wave processes in the CR and common rail injector (CRI), and
- control of several valves of the CRI;
- control of one valve of the CRI.

The wave adjustment of the CR elements is suitable for stationary power plants having a narrow range of operation modes. It requires balancing of the values of volumes of the CRI and CR, lengths of fuel lines with engine operation mode.

Control of several valves mounted in the CRI [4] is aimed either at increase, either at decrease of pressure in the course of fuel injection in relation to pressure in the CR.

Using control of several valves of the CRI, it is possible to provide any desired shape of the front edge of the injection rate. But such CRI have a number of serious drawbacks:
- complicated design and as a consequence – high requirements for manufacturing equipment for attaining the required reliability,
- high price compared with traditional CR, and
- no full compatibility with the existing CR (the presence of a great number of additional parts compared with a traditional CRI injector results either in increasing the size of the injector body, either in using additional external devices which should be taken into account when locating the CR system elements on the engine) – adaptation of engine parts is required.

It is proposed to solve these problems by perfection of the control algorithm of the CRI system controlled by one valve [12, 13]. The advantage of this method is preservation of the traditional design of the CRI.

This paper presents further developments of this method, which makes it possible to distribute fuel by combustion chamber zones.

A method of fuel injection rate shaping and fuel distribution by combustion chamber zones

A method of fuel injection rate shaping of the Diesel engine CR fuel system with CRI and solenoid control is proposed.

The method envisages the impact on control current of impulses applied to the control solenoid valve of the CRI for variation of the injection rate shape. At that, the fuel is supplied via two groups of injection holes, fig. 1. One part of fuel passes through the entry edges of the injection holes of the first group located on the locking cone of the nozzle with axes directed at angles 70-85° in vertical direction. The other part of fuel is supplied through the entry holes of the second group of spraying holes located in the sack volume of the injector

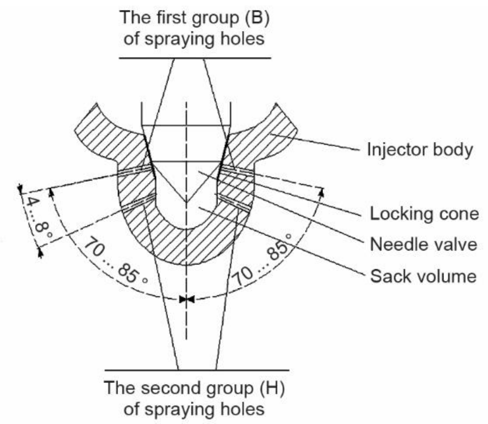

Figure 1. The scheme of directions of nozzle injection holes sprays

nozzle with axes directed at angles in vertical direction by 4-8° smaller than the first group holes.

The angles of the first and second groups of spraying holes were selected by the results of simulation aimed at selection of the *Deep Gesselman* combustion chamber in the piston. When conducting the simulation, the main task was attaining the lowest possible engine brake specific fuel consumption and decrease of particles emission. This challenge was solved by central location of the CR nozzle to ensure uniform fuel distribution over the combustion chamber and getting a smaller portion of fuel whose combustion will be less efficient on its walls.

The technical solution proposed ensures variation of the injection rate shape and uniform distribution of fuel in case of a central location of the injector in the *Deep Gesselman* type combustion chamber in the piston, fig. 2.

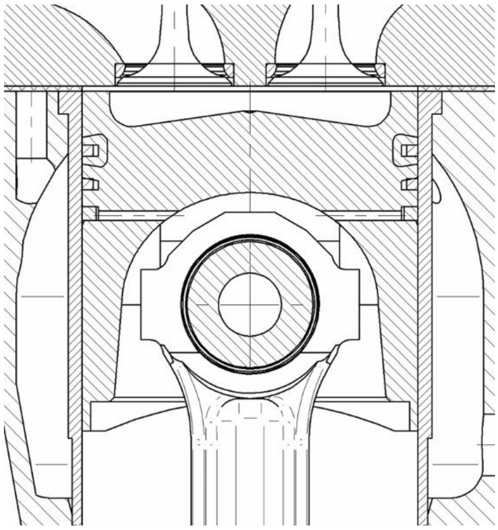

Figure 2. Cross-section Diesel engine with *Deep Gesselman* type combustion chamber

Figure 3 shows the layout of the spraying holes of the CRI nozzle of the first group (B – upper holes) and the second group (H – lower holes) having different total number.

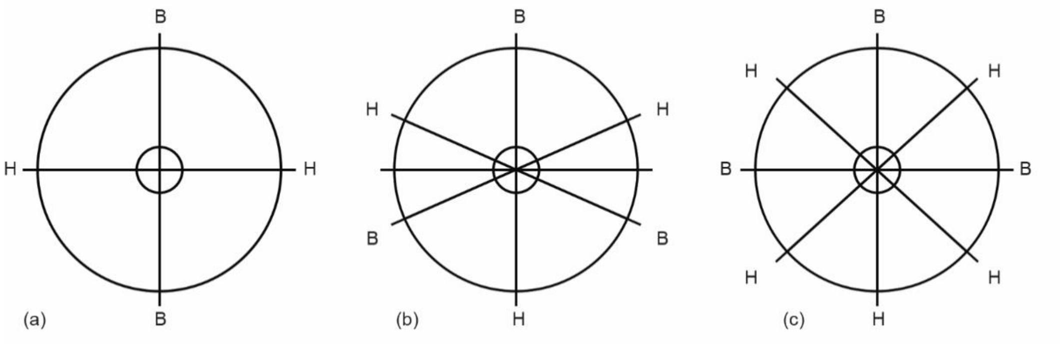

Figure 3. Layout of the spraying holes of the CRI nozzle of the first group (B – upper holes) and second group (H – lower holes) having different total number a – 4, b – 6, c – 8

The method proposed is illustrated by the results, figs. 4-6, obtained with the aid of the modeling complex developed in Moscow Automobile and Road Construction State Technical University for computer modeling of working processes of the CR.

When realizing this method, the closed state of the CRI between injections is maintained by equal pressures in the control chamber volume inside the injector and in the nozzle volume nearby the needle valve. When the control impulse from the electronic control block is applied to the solenoid, the force A developed by it, fig. 4 overcomes the effort of the spring pressing the control valve to its seat, opens the control valve (the lift value h of the control valve grows, fig. 5 and the fuel from the control chamber is drained. As a result, the pressure in the control chamber drops.

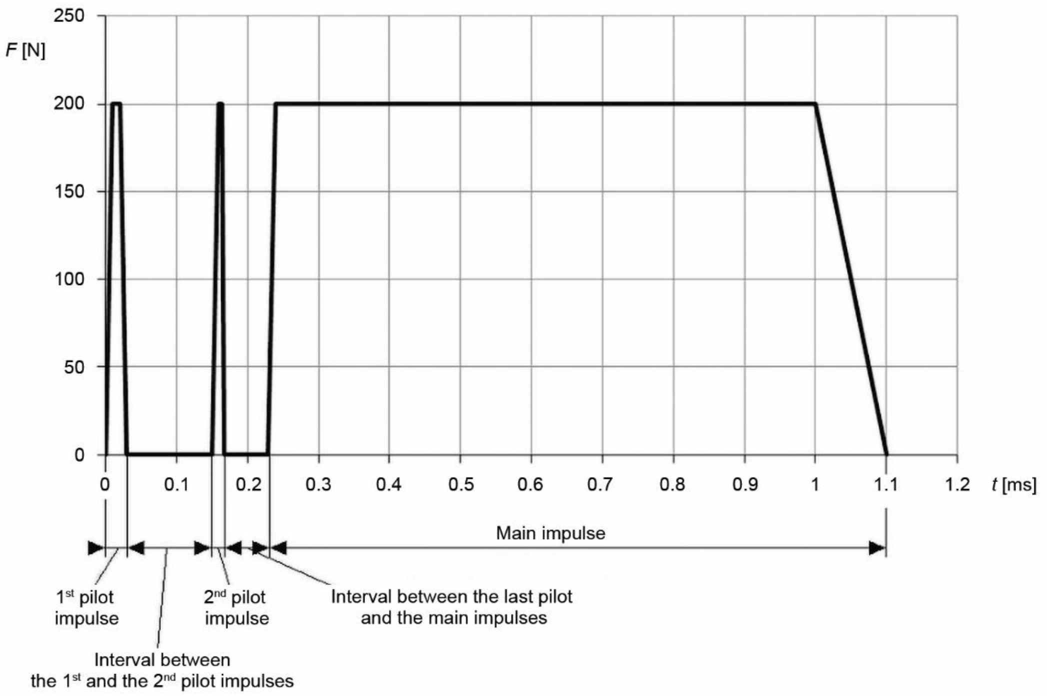

Figure 4. The force *F* of the solenoid formed by two primary and one basic control impulses; *t* – time

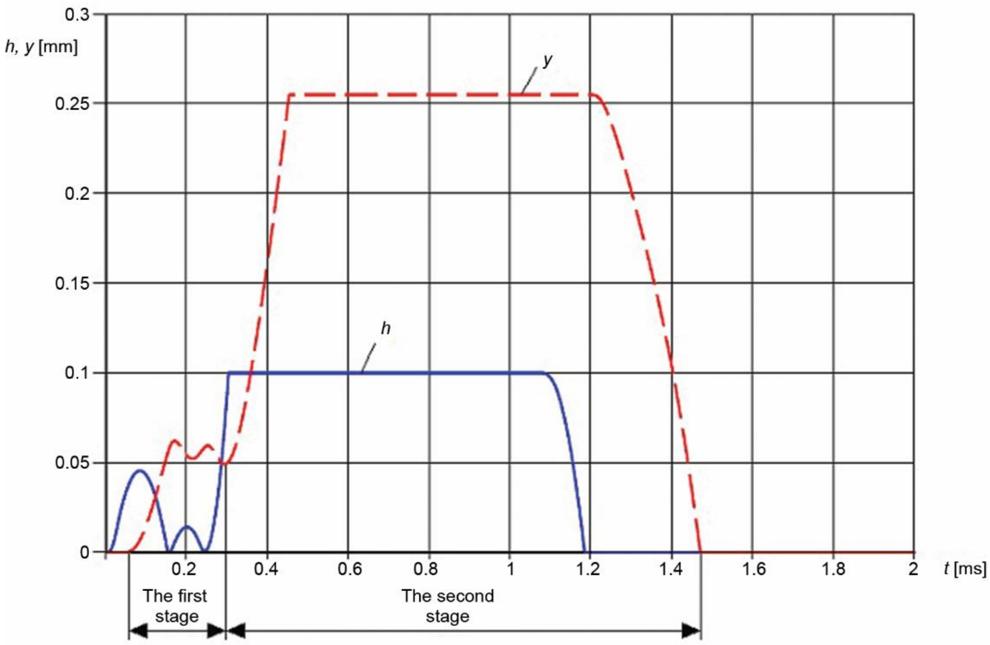

Figure 5. Displacement of the needle valve *y* and control valve *h*

A pressure drop between the injector nozzle volume nearby the needle valve and pressure in the control chamber originates. The needle valve lifts (the nozzle lift value increases, fig. 1) and fuel injection through both the groups of the nozzle holes shown in fig. 1 takes place. As the result of the injection, the injection rate $q(t)$ is formed which is presented in fig. 6.

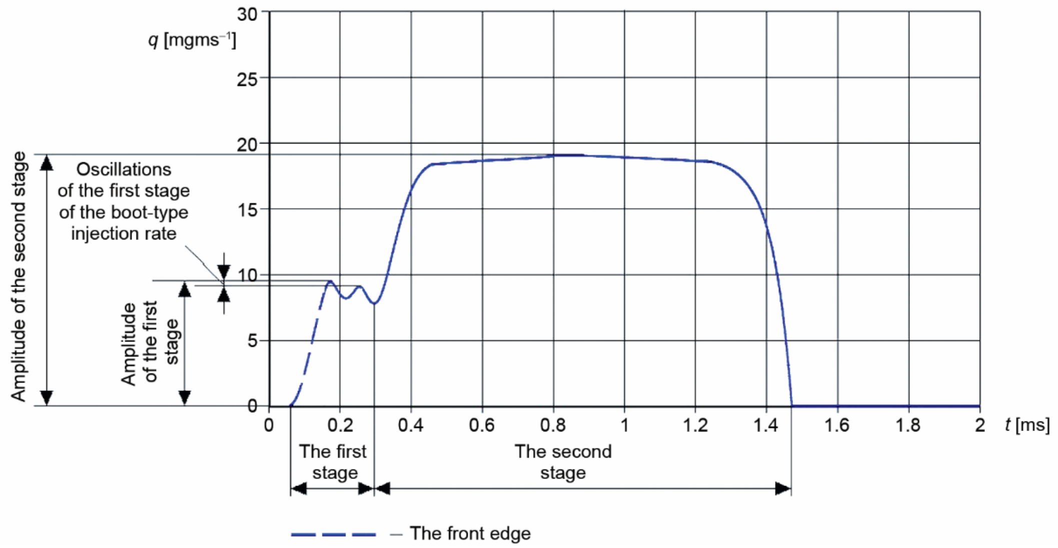

Figure 6. A boot-type injection rate shape $q(t)$, formed by two pilot and one main control impulses; t – time

Due to the difference in position of the entry edges of the holes B and H, fig. 1, at $y < 0.4\ y_{max}$, the fuel velocity and fuel-flow through the spraying holes of the first group (B) differ from the fuel velocity and fuel-flow through the spraying holes of the second group (H).

Taking into consideration the fact that each spraying hole of the CRI nozzle is directed to a certain zone of the *Deep Gesselman* type combustion chamber in the piston, a uniform distribution of fuel in the combustion chamber takes place and injection parameters by its zones are controlled.

After termination of the control impulse current, the solenoid is turned off (F = 0, fig. 4) and the control valve goes down (the h value decreases, fig. 5) by the action of the spring. The value h = 0 corresponds to landing of the control valve on its seat and termination of draining fuel from the control chamber. The pressure in the control chamber grows. The needle valve goes down (the y value decreases, fig. 5). This value corresponds to landing of the valve into the seat in the nozzle body and termination of fuel injection through the spraying holes (q = 0, fig. 6).

If the control current impulse consists of two, fig. 4 or more pilot and one main parts, duration of the first pilot control impulse determines the amplitude of the front edge of the boot-type injection rate $q(t)$. The intervals between the control current impulses are selected in such a way that they ensure the boot-type injection rate with the specified amplitude of oscillations of the first stage of the boot-type injection rate. The amplitude of the first stage of the injection rate is 0.2-0.8 of the amplitude of the second stage of the boot-type injection rate. Oscillations of the amplitude of the first stage of the boot-type injection rate do not exceed 0.10-0.15 of the amplitude of the second stage of the boot-type injection rate, fig. 6.

The fuel-flow speed and flow rate through the holes of the first and second groups depend on the value of y. Therefore, selection of intervals between the control current impulses ensures control of injection by the combustion chamber zones.

Testing set-up

The hydraulic parameters of the nozzle spraying holes are determined at stationary flow of fuel on the test stand shown in fig. 7.

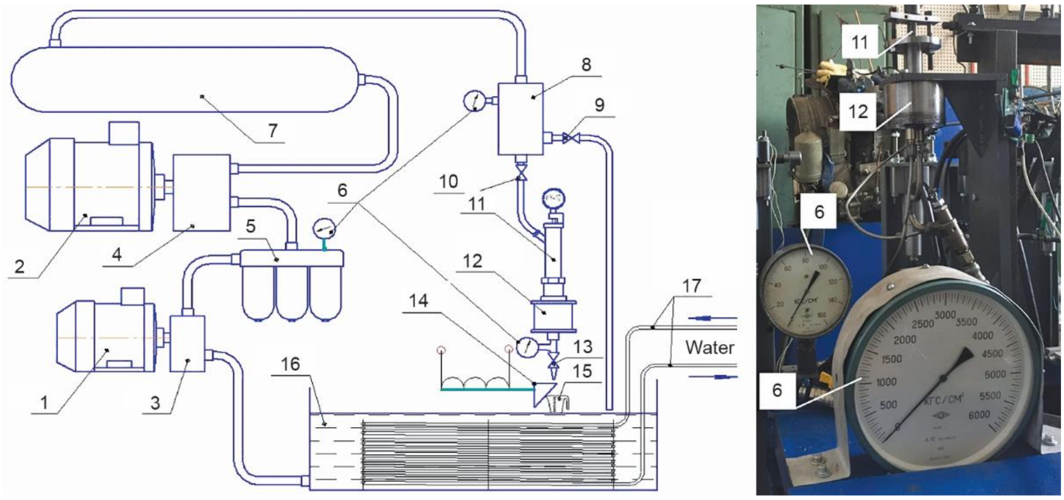

Figure 7. Schematic of the test set-up for determining parameters of injection nozzles; (a) schematic of the test set-up, (b) photograph of the test set-up; *1 – electric motor of fuel feed pump drive, 2 – electric motor of high pressure (HP) fuel feed pump drive; 3 – fuel feed pump; 4 – high pressure pump; 5 – block of fuel fine filters; 6 – indicating pressure gauges; 7 – CR of high capacity; 8 – small common rail; 9 – valve of controlling the volume of bypassed fuel; 10 – throttling valve of injection pressure fine adjustment; 11 – injector body with nozzle and needle valve lift indicator; 12 – chamber; 13 – backpressure adjustment valve in the flow measurement chamber; 14 – electrically driven throttle valve; 15 – measuring volume; 16 – fuel tank; 17 – heat exchanger for cooling fuel*

The test set-up works in the following way. The fuel from the tank 16 is supplied by the fuel feed pump 3 to the high pressure pump 4 via the cascade of fine filters 5. For smoothening the pressure pulsations, the fuel from the high pressure pump is supplied at high pressure via the large volume CR 7 to the smaller volume CR 8 on which the control valves 9 and 10 are mounted.

The required injection pressure is built by variation of the flow section of the bypass valve 9, variation of the amount of fuel drained from the CR 8. The fuel passes via the valve 10 to the injector body with the nozzle tested. Under the action of pressure, the nozzle needle valve raises and fuel enters the chamber 12, filled with fuel. The maximal needle valve lift is set by the stop member (not shown in fig. 7). The pressure in the chamber 12 is controlled by the valve 13. The backpressure value is controlled by the pointer pressure gauge. The fuel from the chamber 12 and common rail 8 is drained back to the fuel tank. A heat exchanger is mounted in the fuel tank. The heat exchanger is cooled by the running water 17 with return of the coolant back into the water-supply system.

The set-up has an automatic system of measuring the amount of fuel passing through the nozzle per unit time. After turning on the time-interval counter (not shown in fig. 7), the throttle valve is moved by a solenoid into the leftmost position ensuring entry of fuel into the measuring volume 15. After the time-interval counter is turned off, the throttle valve drive solenoid is turned off and it returns into the rightmost position redirecting the fuel-flow from the chamber 12 to the fuel tank 16.

Determination of hydraulic characteristics of nozzles

The results of comparison of the coefficients of flow of the spraying holes, μ_{cH}, (for the lower group of holes) and μ_{cB} (for the upper group of holes) at various needle valve lifts are shown in fig. 8 (the coefficient of flow is the ratio of the actual flow rate to the theoretical flow rate that would have occurred in the absence of jet compression).

The comparison is presented for two values of the cavitation number, K_{c}, which is determined as a relation:

$$K_{\mathrm{c}} = \frac{p - p_{\mathrm{c}}}{p_{\mathrm{c}}}$$

where p is the excessive pressure in the common rail 8, fig. 8, and p_{c} – the excessive pressure in the chamber 12.

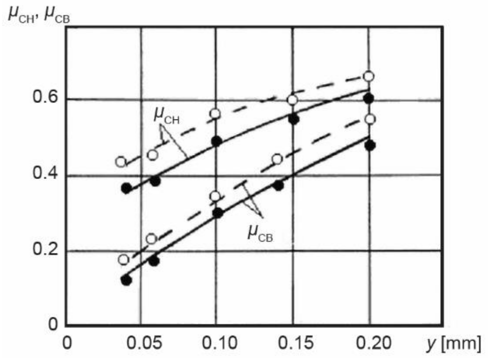

Figure 8. The influence of the needle valve position and cavitation number on the coefficient of flow of the spraying holes; dash line – K_{c} = 3, full line – K_{c} = 60

The coefficients of flow μ_{cH} and μ_{cB} differ considerably and depend on the position of the needle valve. At $y > 0.2$ mm, $\mu_{cH} > \mu_{cB}$ by 10 … 20%, at $y < 0.1$ mm, $\mu_{cH} > \mu_{cB}$ 2 … 3 times. This predetermines correction of the fuel delivery by the spraying holes and hence, by the combustion chamber zones.

In this way, the design of the nozzle shown in fig. 1 makes it possible to use more efficiently the air contained in the combustion chamber. The holes of the first group μ_{cH} are directed at the remote walls of the combustion chamber located in the piston and the holes of the second group μ_{cB} – at the nearby walls.

To estimate the influence of the injection pressure on variation of the coefficient of flow of the spraying nozzles in the process of injection into the engine cylinder, tests of experimental nozzles having 8 spraying holes with entering edges located in the sack volume were carried out. The nozzle versions had different spraying hole diameter, d_{c}: 0.12, 0.13, and 0.135 mm.

During the tests, the pressure, p, varied in the range from 30 to 150 MPa, and p_{c} varied from 0 to 16 MPa.

The results of tests of the nozzle having d_{c} = 0.13 mm are shown in fig. 9.

In the course of raising pressure in the chamber 12, fig. 7, the μ_{c} value varies. The pattern of this variation depends on injection pressure, p. At p = 30 MPa, μ_{c} increases from 0.716 to 0.738 in the range of K_{c} is 29 … 149. Decrease of K_{c} lower than 29 is accompanied with the decrease of μ_{c}. In case of p = 150 MPa, the aforementioned inflection takes place at lower value K_c = 11.5, and at p = 100 MPa, the inflection does not take place in the K_c variation range from 8.38 to 249.

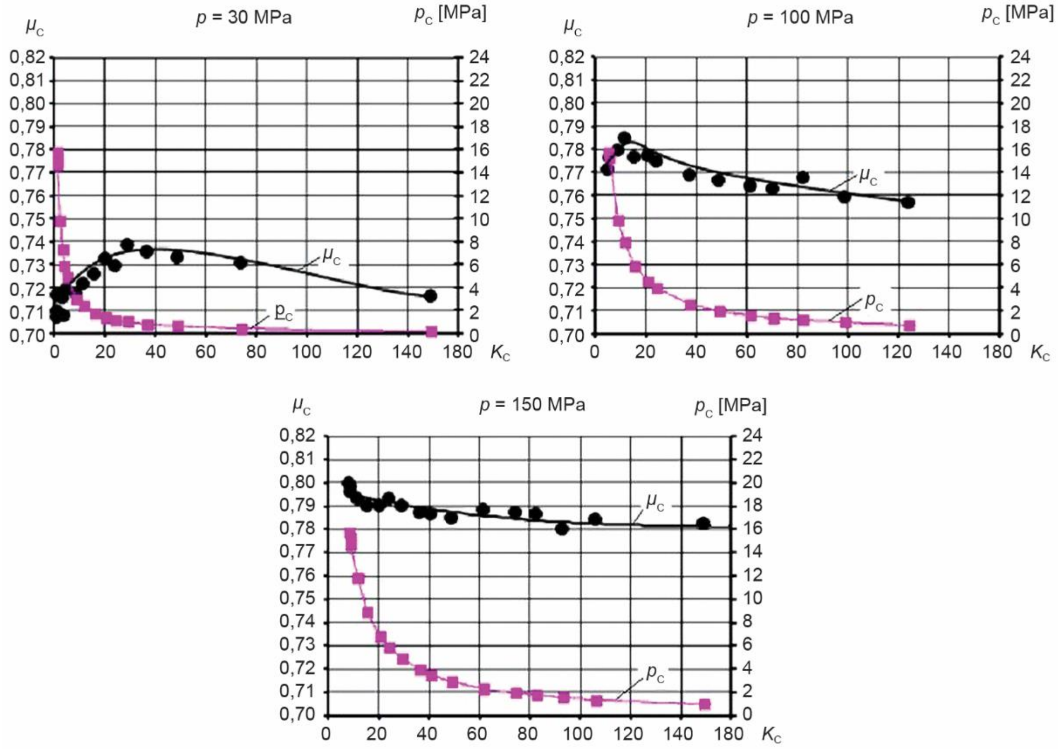

Figure 9. Dependence of the flow coefficient, μ_c, of the injector nozzle spraying holes on the cavitation number, K_c, at d_c = 0.13 mm

It should be mentioned that the μ_c variation range narrows as the pressure, p, increases. So at p = 30 MPa, this range is from 0.707 to 0.738, that is, variation of μ_c is 4.4%. If the pressure, p, is increased to 150 MPa, the range of μ_c will be from 0.78 to 0.8 (2.6%).

As the injection pressure p is increased at constant K_c, the effective flow section $\mu_c f_c$ of the nozzle holes increases, fig. 10.

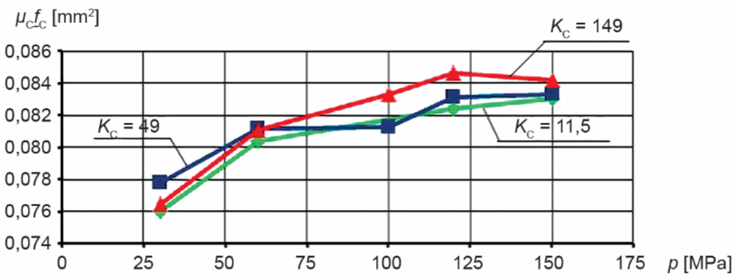

Figure 10. Dependence of the effective flow section $\mu_c f_c$ of the injector nozzle spraying holes (d_c = 0.13 mm) of its inlet pressure at constant value of the cavitation number, K_c

With decrease of the diameter, d_c, at constant value of K_c and pressure, p, the value of μ_c increases, tab. 1. So at K_c = 11.5 and p = 30 MPa, variation of d_c from 0.13 to 0.12 mm resulted in the increase of μ_c by 5.1%. The similar variation of temperature at K_c = 11.5 and p = 60 MPa was 2.2%.

Table 1. Dependence of the coefficient of flow, μ_c, on the spraying holes diameter, d_c, and injection pressure, p

K_c	p = 30 MPa		p = 60 MPa	
	d_c = 0.13 mm	d_c = 0.12 mm	d_c = 0.13 mm	d_c = 0.12 mm
	μ_c		μ_c	
11.5	0.721	0.758	0.764	0.781
49	0.733	0.775	0.765	0.776
149	0.716	0.755	0.758	0.778

Conclusions

- A method of injection rate shaping by an electric impulse, which is applied to the control valve solenoid of the CRI is proposed. Electric impulse consists of two and more primary impulses and one main impulse. Duration of the first primary control impulse determines the amplitude of the front edge of the first stage of the boot-type injection rate shape. The intervals between the control impulses in case of a multiple injection are selected so that to assure a boot-type of injection rate shape with the desired value of oscillations of the first stage of the boot-type fuel injection rate shape.
- In nozzles with two groups of holes (correcting nozzles), the coefficient of flow of the holes in the sack volume μ_{cH} and on the locking cones of the needle valve μ_{cB} differ considerably and depend on the needle valve position. It creates opportunities for correction of the fuel supply by spraying holes and hence, by the combustion chamber zones taking into account the operation mode of the Diesel engine.

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Nomenclature

B – upper spraying holes, located on the locking cone of the injector nozzle
d_c – spraying hole diameter, [mm]
F – force of the solenoid, [N]
H – lower spraying holes, located in the sack volume of the injector nozzle
h – displacement of the control valve, [mm]
K_c – cavitation number, [–]
p – excessive pressure in the CR, [MPa]
p_c – excessive pressure in the chamber, [MPa]
$q(t)$ – injection rate, [mgms^{-1}]
t – time, [ms]
y – displacement of the needle valve, [mm]

Greek symbols

μ_c – coefficient of flow of the spraying holes, [–]
$\mu_c f_c$ – effective flow section of the spraying holes, [mm^2]
μ_{cB} – coefficient of flow of the spraying holes, located on the locking cone of the injector nozzle, [–]
μ_{cH} – coefficient of flow of the spraying holes, located in the sack volume of the injector nozzle, [–]

Abbreviations

CR – common rail
CRI – common rail injector

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