EXPERIMENTAL STUDY OF THE INFLUENCE OF PRESSURE OSCILLATIONS IN COMMON RAIL INJECTOR ON FUEL INJECTION RATE

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The article presents the results of various factors influence experimental research on pressure oscillations at the injector inlet in case of single and double injections of different fuels. With this, such factors as fuel pressure, injection rate value, interval between injections, physical properties of fuel and design features of the injector were taken into account. The aim of the research: to evaluate the influence of pressure oscillations caused by the preliminary injection of fuel to the main injection. Analysis of the experimental data obtained is useful for selection of main design solutions for Common Rail Injectors (CRI).

Key words: common rail type fuel system, common rail injector, hydrodynamic effects, pressure oscillations, fuel injection rate

1. Introduction

As fuel systems are improved, the maximal injection pressure grows [8, 10]. In a number of publications, the issue of the need of injecting fuel under the pressure over 2500 bar is discussed [5, 6, 7, 9].

The pressure growth in case of multiple injection makes the fuel injection working process more complicated. Pressure oscillations at the injector inlet become more crucial which was noted by many researchers [1, 2, 3] including in Moscow Automobile and Road Construction State Technical University (MADI).

In publication [2] the influence of hydrodynamic effects in the fuel line on pressure oscillations in the CRI inlet is investigated.

The oscillations grow as the channel length increases and diameter decreases. But the fuel line also influences on their frequency. For example if the fuel line length increases, the frequency decreases. This is explained by the fact that pressure wave travel time in a long channel is higher. Oscillation process increases with the growth of fuel pressure in the common rail and control impulse duration.

It is demonstrated that depending on the interval between two portions of double injection, the injection rate may vary considerably. The wave process that originates when one CRI injects fuel has an impact on fuel injection process of other diesel engine cylinders' injectors.

In publication [1], a conclusion is made on the reasons of pressure oscillations: pressure oscillations, which are triggered by nozzle-closure induced water-hammer, at the end of each injection

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event. When fuel is flowing via nozzle holes during injection process, its kinetic energy grows which is transformed into energy of pressure waves when the needle valve closes and the flow stops abruptly.

In publication [3] it was found that fuel pressure oscillations can't be the reason of resonance of fuel system mechanical parts because their natural oscillation frequency is considerably lower than the frequency of wave process in hydraulics. However one demonstrated the possibility of the origination of hydraulic resonance which takes place when: needle closes as soon as the compression wave, due to the rail reflection of the injection-induced depression wave, reaches the nozzle.

When the needle valve seats on its seat, the hydraulic impact takes place. The pressure wave and the direct pressure wave (compression wave) which originate, as a consequence, appear to be in the same phase which causes intensive pressure oscillations in the delivery line. It is important to take into consideration this effect in case of multiple injection and seek to avoid it.

The analyses of the influence of injector design on wave process is of interest. For example, it is demonstrated here that in a nozzle having holes on the locking cone, the hydraulic impact when the injector is closing is not so strong as in case of a nozzle having holes in the sack volume.

The results described need to be supplemented by data on ways of prevention of oscillation effects and the influence of fuel properties on them. The present article reflects the results of solving these scientific tasks.

2. Experimental set up

The experimental set up (Figure 1) has modular design making possible its adaptation for current research tasks and various designs of fuel systems. This set up contains of:

- asynchronous electric motor 3 (7.5 kW, 3000 rpm) with a thyristor transducer 12 enabling a smooth control of rotation speed;
- low pressure fuel line which includes a low pressure fuel pump 16, 12 V and 24 V electric power supply units 8 - 9, fine fuel filter 15.

The fuel system (Figure 2) of the experimental set up includes: radial-plunger type high pressure fuel pump 1 with throttle valve for fuel entering the pump, fuel accumulator 2 with pressure sensor 16 and two electro-hydraulic injectors 3.

In both injectors, electromagnetic drive of the control valve is used. The second injector differs from the first one with the presence of a fuel accumulator integrated into the body and the design of the pressure balanced valve. Layouts of the injectors are presented in Figure 3. Parameters of its elements are presented in Table 1.

For carrying out investigations, experimental set up was complemented with measuring system having two piezoelectric sensors. The first sensor is mounted at the inlet of the common rail injector (CRI) and registers the pressure oscillations when fuel is injected. The second sensor is mounted in the chamber and registers the instants of fuel injection start and end. The chamber presents an enclosed volume with a pressure discharge valve. The measuring system components are presented in Table 2.

The magnitude of fuel injection rate Q measured by the gravimetric method. When determining the Q of each point measurement is carried out twice, which allows to determine the random measurement error of this magnitude (ΔQ). The instrument error of high-precision scales is neglected since its value is substantially less random measurement error.

Each measurement provides ΔQ not lower than ±5,0%, which is achieved by selecting a sufficient number of cycles.

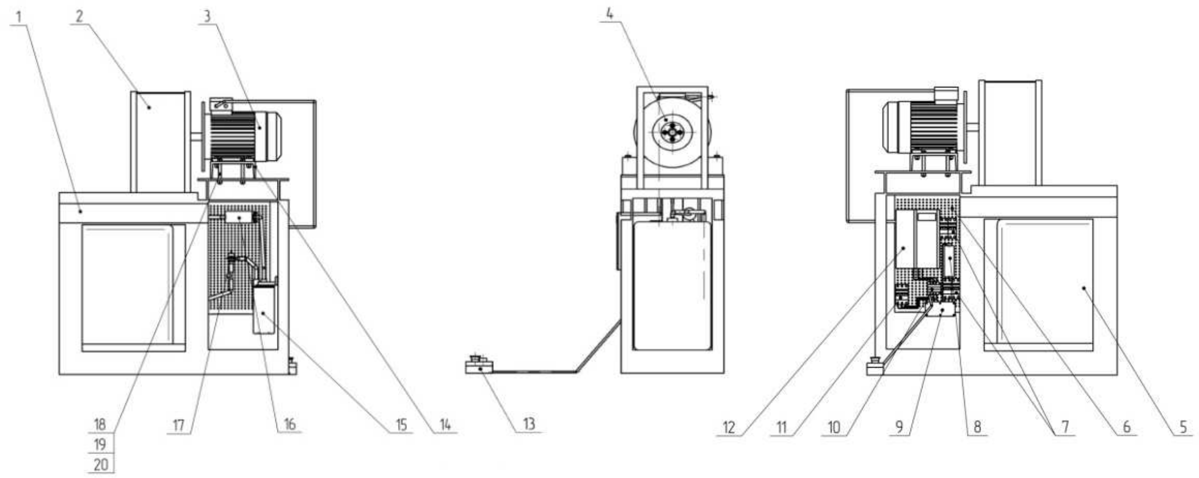


Fig. 1. Experimental set up:
1 – frame; 2 – protective casing; 3 – asynchronous electric motor; 4 – coupling; 5 – fuel tank; 6 – mounting plate; 7, 11 – fuses; 8, 9 – electric power supply units; 10 – magnetic contactor; 12 – thyristor transducer; 13 – emergency stop switch; 14 – electric motor mounting; 15 – fine fuel filter; 16 – low pressure fuel pump; 17 – pressure regulator; 19, 20 – mounting the motor to the frame

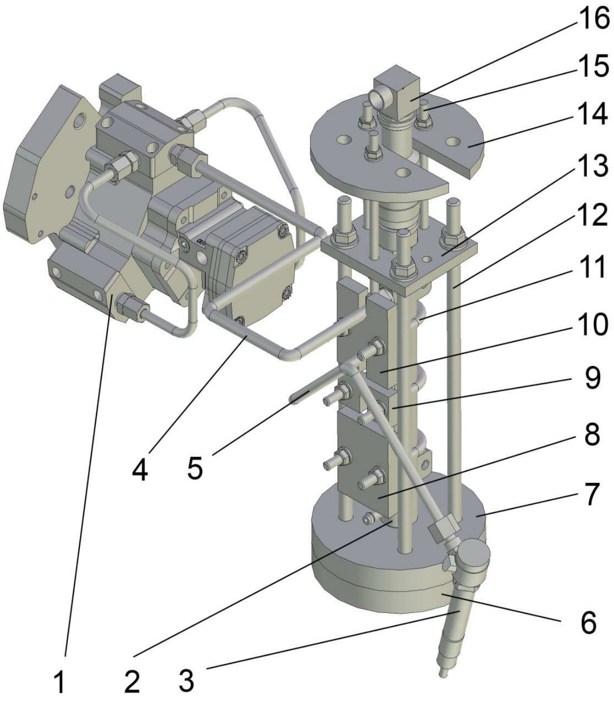


Fig. 2. Fuel system of the experimental set up:
1 – high pressure fuel pump; 2 – fuel accumulator; 3 – electro-hydraulic injector; 4, 5 – high pressure fuel lines; 6, 7 – mounting plates of the fuel accumulator; 8, 9, 10, 14 – clamping plates; 11 – fixings; 12 – fixing pin of the fuel accumulator; 13 – mounting plates of the pressure sensor; 15 – fixing pin of the pressure sensor; 16 – pressure sensor

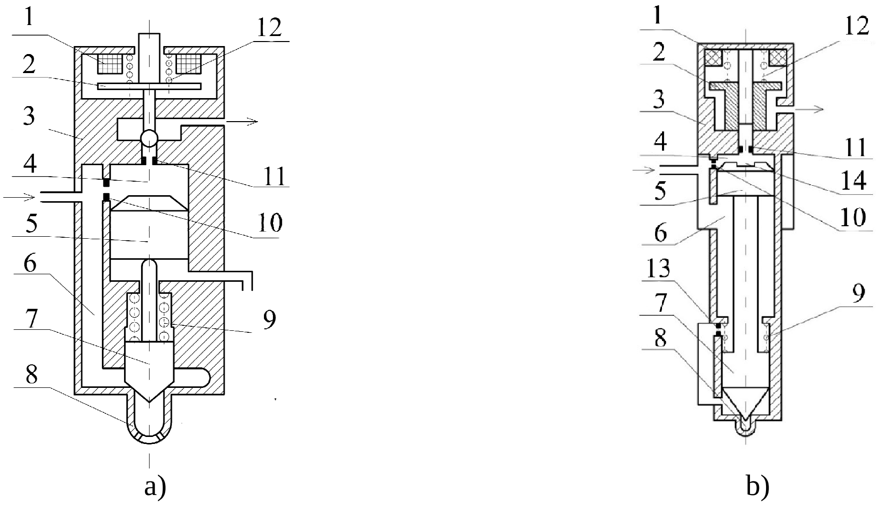


Fig. 3. Layouts of the injectors: a – injector No1, b – injector No2;

1 – solenoid, 2 – control valve, 3 – CRI body, 4 – control chamber, 5 – multiplier (for version b, elements 5 and 7 are one piece); 6 (a) – channel supplying fuel to the injector nozzle; 6 (b) – fuel accumulator; 7 – injector nozzle needle; 8 – injector nozzle; 9 – needle spring; 10 – inlet throttle; 11 – outlet throttle; 12 – valve spring; 13 – additional throttle; 14 – channel

Table 1. Basic parameters of fuel system elements

Fuel system element	Parameters
CRI No1	No integrated fuel accumulator, pressure unbalanced valve, fuel injector nozzle hole diameter d_c=0.12 mm, number of holes 7.
CRI No2	Integrated fuel accumulator is present, pressure balanced valve, fuel injector nozzle hole diameter d_c=0.09 mm, number of holes 8.
Fuel line	Fuel line 5 (Figure 2) length l_{fl}=1000 mm, channel diameter d_{fl}=2.2 mm.

Table 2. Measuring equipment

Name	Tool description
AVL A03 (Austria)	Dual-channel charge amplifier.
T6000 No 4636 (Russia)	Piezoelectric sensor. Sensibility: 2.1 pC/bar. Pressure measuring range 0…6000 bar.
T6000 No 4588 (Russia)	Piezoelectric sensor. Sensibility: 2.2 pC/bar. Pressure measuring range 0…6000 bar.
DMP304 (Germany)	Strain-gage sensor. Pressure measuring range 0…4000 bar.
Siglent AKIP 4126/2 (China)	Digital storage oscilloscope.

The measurement error of the inlet pressure in the injector and fuel accumulator is determined by the accuracy of measuring instruments. Therefore, calibration of pressure sensors T6000 and DMP304 (Table 2) were previously conducted.

Electronic control of fuel system is effected with the aid of microprocessor control system developed in MADI. Measurement of injection rates was carried out using Collection of fuel for measuring injection rates is carried out with laboratory graduated jars.

The experiment was carried out in two stages: the first stage – the injector operate in case of a single injection; the second stage – the injector operate in case of multiple injection.

3. Results and Discussion

At the first stage, the influence of the following factors on pressure oscillations at the CRI inlet was investigated (Figure 4): fuel pressure p_{ac}, control impulse duration τ_{imp}, type of fuel used. With this, two different injectors having principally different design were estimated in the experiment.

As fuel were used diesel fuel and sunflower oil (Table 3).

Table 3. Properties of the fuels used

Properties	Diesel fuel	Sunflower oil
Density (t = 20 ºC), кg/m^3	820	923
Kinematic viscosity (t = 20 ºC), mm^2/c	3.0	65.2
Cetane number	45	33
Low calorific value, MJ/kg	42.5	37.0

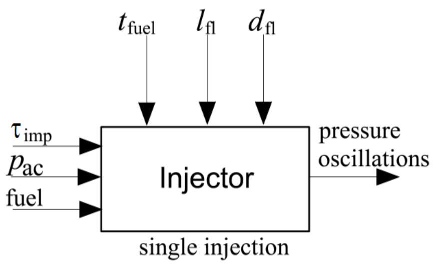


Fig. 4. Layout of the first stage of the experiment:

controlled factors: τ_{imp} – control impulse duration, p_{ac} – pressure in the fuel accumulator, fuel – working fluid (diesel fuel or sunflower oil); uncontrolled factors: t_{fuel} – fuel temperature, l_{fl} – fuel line length, d_{fl} – fuel line diameter

Fuel injection causes considerable oscillations of fuel pressure at the injector inlet. One of the reasons is hydraulic impact originating when closing the injector nozzle needle. In this way, in the injector No1 with pressure p_{ac}=1000 bar and control impulse duration τ_{imp}=0.6 ms (corresponds to fuel injection rate Q=16.5 mg), the injection causes pressure oscillations with amplitude up to 250 bar (Figure 5). Evidently, these oscillations influence the fuel supply process in case of multiple injections: the previous injections would influence on the following ones.

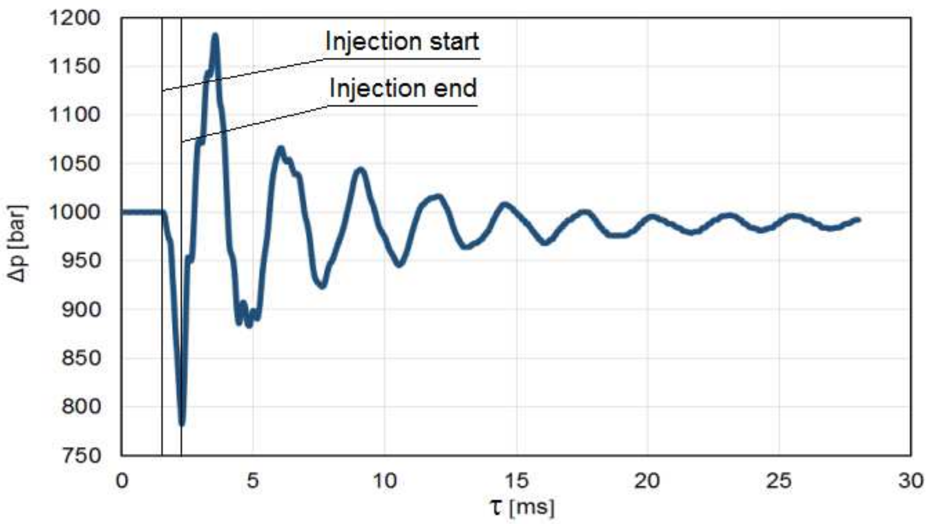


Fig. 5. Pressure at the inlet of the CRI No 1 (p_{ac}=1000 bar, τ_{imp}=0.6 ms, Q=16.5 mg)

As the fuel pressure and injection rate increase, the oscillation process increases. Figure 6 shows the comparison of data at three pressures in the fuel accumulator and constant control impulse duration τ_{imp} =0.6 ms. A single injection is used. The pressure oscillation range at the CRI inlet at p_{ac}=1500 bar is up to 350 bar, and at p_{ac}=500 bar, the amplitude decreases to 80 bar.

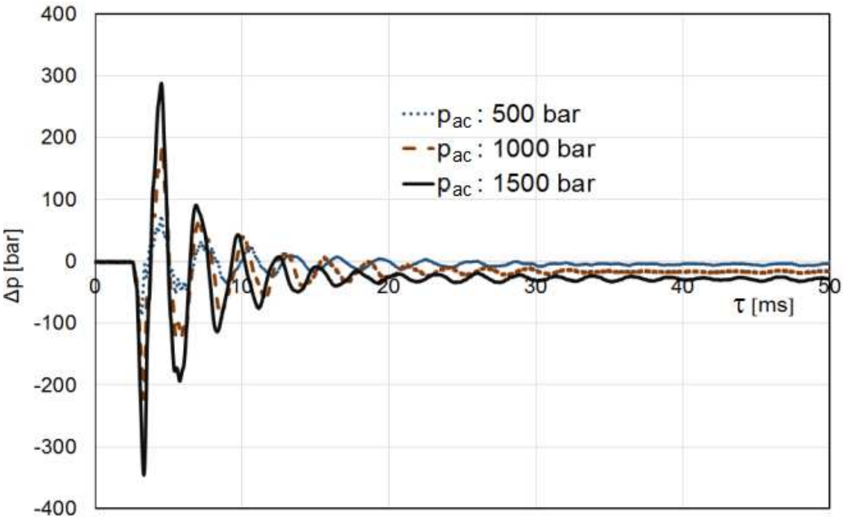


Fig. 6. Fuel pressure oscillations at the entry of the CRI No1 at various pressures (τ_{imp}=0.6 ms): Q=9.1 mg (p_{ac}=500 bar); Q=16.5 mg (p_{ac}=1000 bar); Q=38.3 mg (p_{ac}=1500 bar)

Figure 7 shows the comparison at constant pressure in the fuel accumulator p_{ac}=1000 bar and variation of the first control impulse duration. On the basis of this, one can make a conclusion that as the first portion of fuel decreases, the oscillations range also decreases.

Figure 8 shows the data for the injector No2 at the operation mode p_{ac}=1000 bar and τ_{imp}=0.6 ms. Compared with the No1 version of the CRI (Figure 5), the pressure oscillations are considerably lower. The pressure oscillations range for the version No1 is 400 bar, and for the version No2 – 120 bar, that is, 3.3 times lower. Hence, the internal volume of the injector plays a considerable role and may be an efficient measure for lowering pressure oscillations.

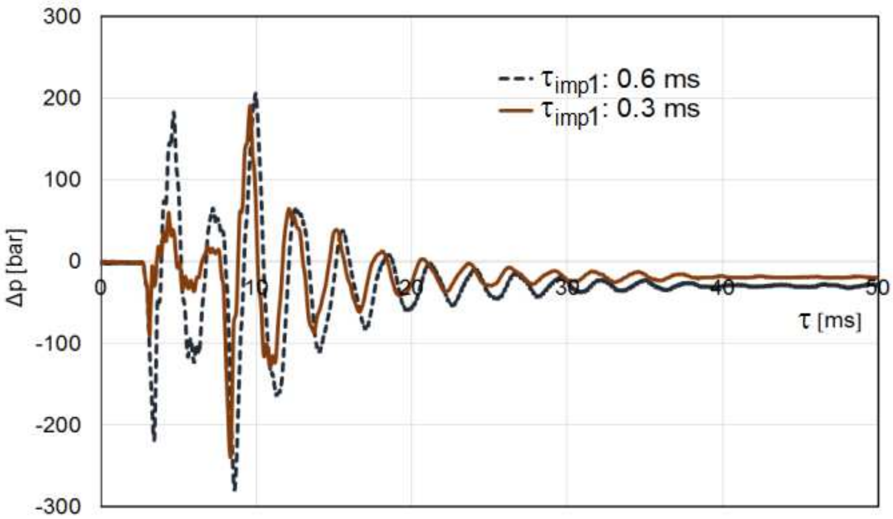


Fig. 7. Fuel pressure oscillations at the entry of the CRI No1 at various duration of the first injection (p_{ac}=1000 bar): Q=2.2 mg (τ_{imp}=0.3 ms); Q=16.5 mg (τ_{imp}=0.6 ms)

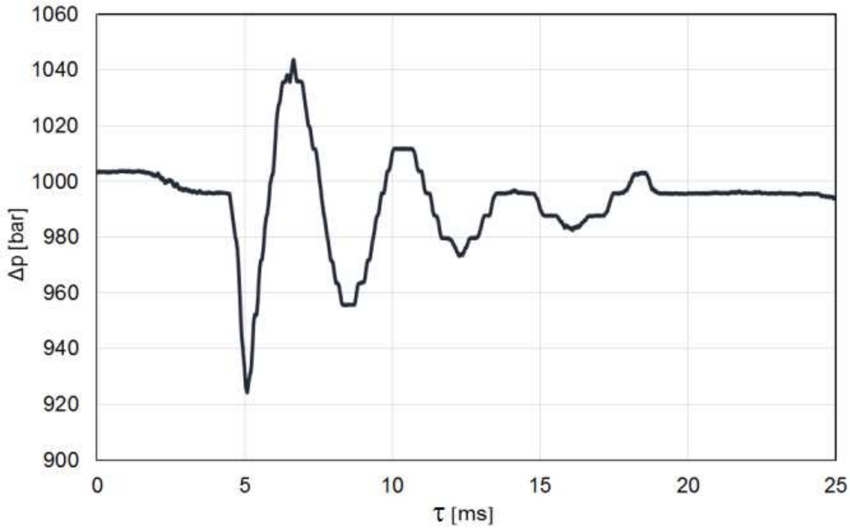


Fig. 8. Pressure at the inlet of the CRI No2 (p_{ac}=1000 bar, τ_{imp}=0.6 ms, Q=24.0 mg)

The injector No2, has a pressure balanced valve in addition to integrated fuel accumulator. The balanced valve makes it possible not only to decrease the volume of fuel leaks at high pressure, but also to improve the injector working process in case of multiple injection [4].

Physical properties of fuel used are also important in case of fuel injection. As the viscosity of fuel increases, the hydraulic friction grows which contributes to rapid damping of oscillations. Figure 9 shows the data for the injector No1 when operating on sunflower oil. As compared with diesel fuel (Figure 5), the oscillations range decreases from 400 to 250 bar at the same operating mode.

At the second stage, the influence of the interval between the impulses of a double injection on the injection rate value of the second portion was investigated. In this experiment, the injector No1 was used. The layout of the second stage of the experiment in case of a double injection is presented in Figure 10.

The oscillogram of a current passing through electric magnet of injector No1 is shown in Figure 11. The injector control is carried out in two phases: forcing and holding. For forcing, voltage of about 50 V is applied to the electric magnet during 0.3 ms which promotes a rapid raise of the control valve. The injector needle is held using pulse-width modulation with duty ratio 50%.

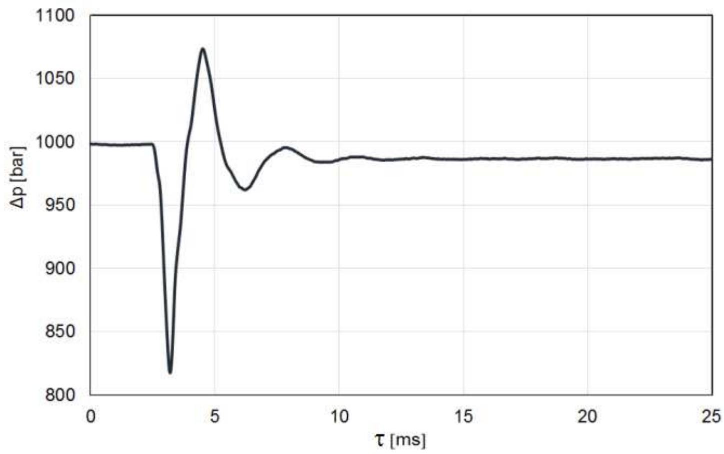


Fig. 9. Pressure at the inlet of the CRI No1 (p_{ac}=1000 bar, τ_{imp}=0.6 ms, Q=15.9 mg), operation on sunflower oil

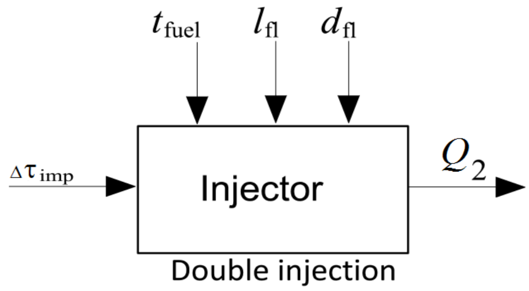


Fig. 10. Layout of the second stage of the experiment:

controlled factor: $\Delta\tau_{imp}$ – interval between two portions of a double injection;

uncontrolled factors: t_{fuel} – fuel temperature, l_{fl} – fuel line length, d_{fl} – fuel line diameter;

output parameter: Q_2 – injection rate of the second portion of a double injection

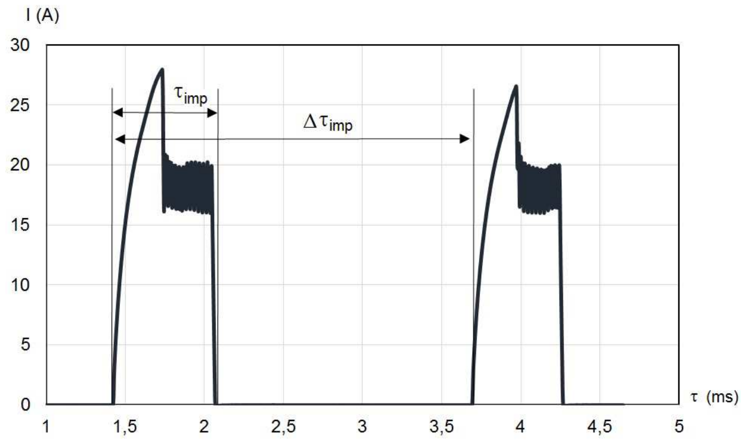


Fig. 11. Oscillogram of current passing through electric magnet of injector No1 (double injection): τ_{imp} – control impulse duration, $\Delta\tau_{imp}$ – interval between two portions of double injection

Injector rate and injection characteristic of the second portion depend on the time at which the second injection is effected related to the first one. Figure 12 shows the results of the investigations at constant pressure p_{ac}=1000 bar, two injections each having τ_{imp}=0.6 ms with variable interval $\Delta\tau_{imp}$. The vertical line designates the instant of fuel portion injection start.

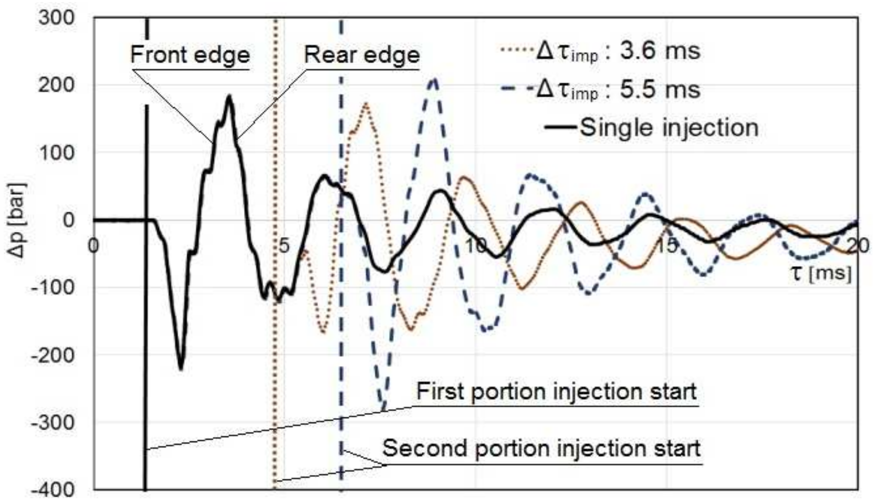


Fig. 12. Pressure oscillations at the inlet of CRI No1 at various intervals between double injection $\Delta\tau_{imp}$ (p_{ac}=1000 bar): Q=17.5 mg ($\Delta\tau_{imp}$=3.6 ms); Q=9.5 mg ($\Delta\tau_{imp}$=5.5 ms)

The superposition of waves in case of multiple injection may result both in amplification and damping of oscillations process. If the second injection is executed at the rear wave edge (pressure increase) or in the zone of minimum – the oscillations damping takes place. If the second injection is executed at the front (decreasing) wave edge or in the zone of maximum, the oscillations increase.

Figure 12 shows that at the interval $\Delta\tau_{imp}$=3.6 ms, after injection of the second portion, the maximal pressure oscillations range is 330 bar. At the interval $\Delta\tau_{imp}$=5.5 ms, the maximal range increases 1.45 times to 480 bar.

Figure 13 shows the results of estimation of the dependence of the injector rate Q of the second injection on the interval between injections. The first injection value is constant and amounts to Q_1=16.5 mg. The difference between the first and the second magnitudes of the injection rate is almost 2 times.

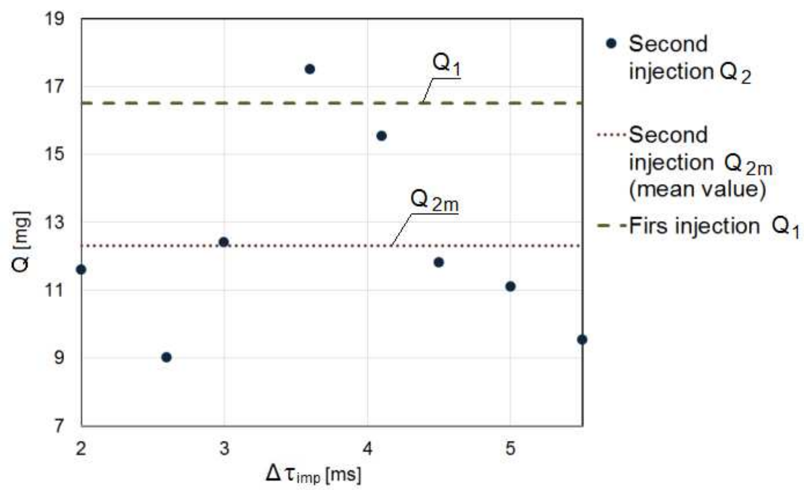


Fig. 13. Fuel injection rate at various intervals between injections $\Delta\tau_{imp}$ (p_{ac}=1000 bar, τ_{imp}=0.6 ms)

It should be mentioned that the average value of the second injector rate is considerably lower than of the first one.

Even if the beginning of the second injection is shifted removed from the first injection to the interval $\Delta\tau_{imp}$ =50 ms, the value of the second portion is 13.1 mg which is by 3.4 mg lower than the first one though the pressure oscillations of the first injection are damped completely during 50 ms.

This phenomenon have two explanations.

First, the pressure in the fuel accumulator drops after the first injection. The pressure deviation value is not large and according to data presented in Figures 5…6, amounts to 50 bar (depending on operation mode).

The second factor is voltage slump on the injectors power supply condenser. It follows from Figure 11 that forcing current of the second injection is by 2.5 A lower than the first one which promotes the longer opening of the injector.

In this way, modern injection system also makes stringent requirements to such parameters as fuel pressure control dynamics and charging the power supply condenser of the injectors.

Injection characteristic of the second fuel portion also depend on $\Delta\tau_{imp}$ because the pressure in the needle volume is interlinked with the pressure at the inlet of the CRI. For example, if the injection of the second fuel portion starts in the zone of pressure wave minimum and terminates in the zone of maximum (Figure 12), the fuel flow velocity through the spray holes will vary during the injection process from low to high.

Simulation was carried out to estimate the influence of fuel type and time interval $\Delta\tau$ (Figure 14) between control impulses of double injection on the value of the injection quantity of the second portion at pressures 2000…3000 bar.

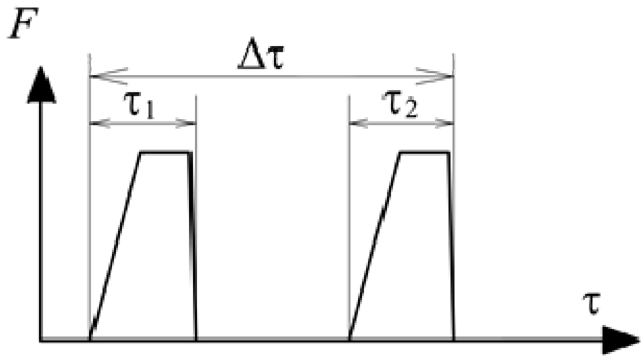


Fig. 14. Control impulses modeled: *F* – injector electromagnet force, $\Delta\tau$ – time interval between control impulses, τ_1 – first control impulse duration, τ_2 – second control impulse duration

The simulation was carried out using the software package which is being developed in MADI.

The CRI No2 was selected as a subject of research, because it is providing a smaller pressure oscillations range.

The flow chart of the simulation is shown in Figure 15. Two equal control impulses were modeled (τ_1 = τ_2). Duration of the control impulses τ was selected such that the fuel quantity supplied during the first injection was $Q_1 \approx$ 3…4 mg.

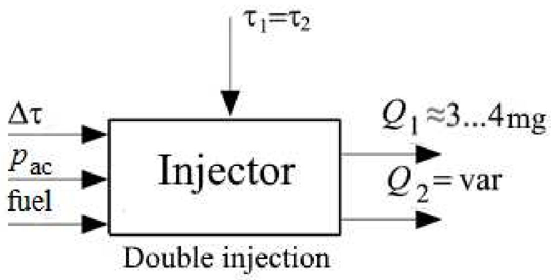


Fig. 15. Test flow chart: Q_1, Q_2 – injection rate values of the corresponding portions

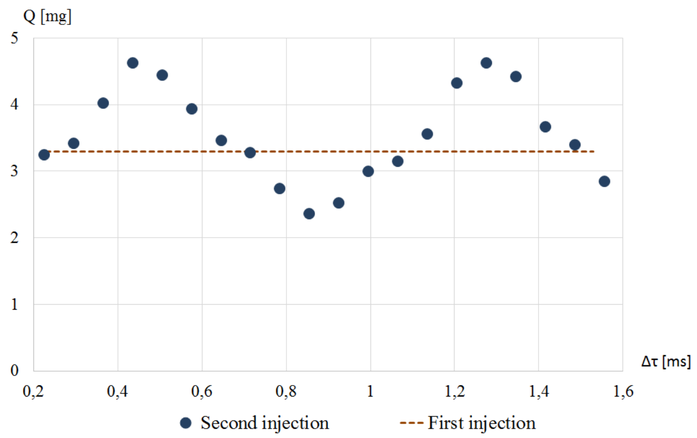
Computation results of operation of the CRI No2 on diesel fuel are presented in Figure 16.

As was demonstrated during experimental tests (Figure 13), the reason of variation of injection rates versus $\Delta\tau$ were pressure oscillations at the inlet to the injector.

When the pressure p_{ac} grows, the oscillation phenomenon and its impact on the working process increase. When operating on diesel fuel at pressure p_{ac}=2000 bar, the spread in injection rates of the second portion is Q_2 = 2.36…4.62 mg, and at p_{ac}=3000 bar Q_2 = 1.58…6.63 mg.

The results of imitation carried out for a more dense fuel corresponding to sunflower oil are presented in Figure 17.

a)



b)

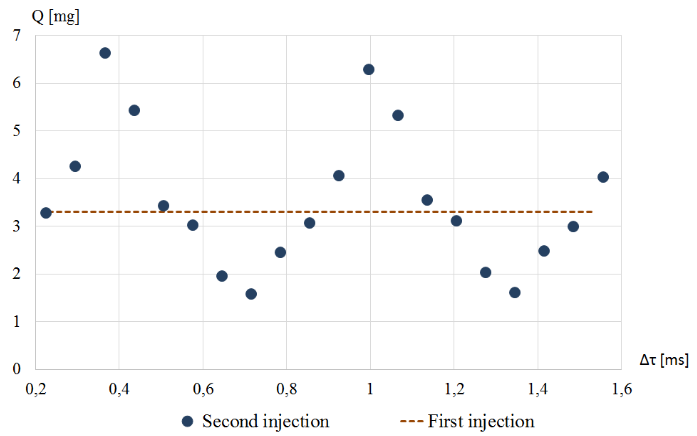


Fig. 16. Fuel injection rate Q_2 at different intervals between injections $\Delta\tau$ for diesel fuel (Q_1 =3.3 mg): a – p_{ac}=2000 bar, b – p_{ac}=3000 bar

The main difference of Figure 14 from Figure 15 is a faster attenuation of oscillations observed when passing to a more dense fuel. In case of p_{ac}=2000 bar, the spread in injection rates of the second portion is Q_2 = 2.96…4.21 mg, and at p_{ac}=3000 bar – Q_2 = 2.42…5.50 mg.

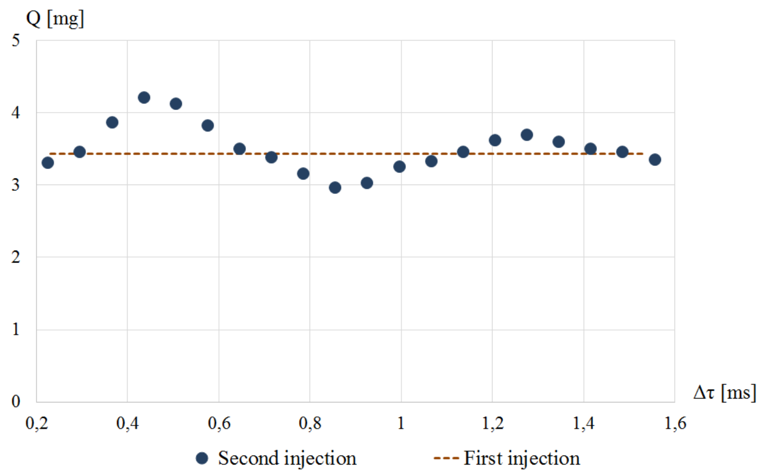
It is seen from comparison of calculated data (Figure 16 and Figure 17) that due to a higher hydraulic friction, the maximal pressure oscillations range is lower. This will have a positive effect on the control precision of the second portion of fuel injected.

Conclusions

1. Fuel injection causes considerable pressure oscillations at the inlet of the injector. The oscillations range depends on: injection pressure, control impulse duration, fuel physical properties and injector design. One of the reasons of oscillations is hydraulic impact which takes place when the injector needle closes.

2. The pressure drop in the accumulator after preliminary injection (the amount of deviation of the pressure is 5 MPa depending on the mode) and the voltage drop across the capacitor of the power injector (the current boost of the second injection of 2.5 A less than the first) favors longer opening of injectors in case of next injection.

a)



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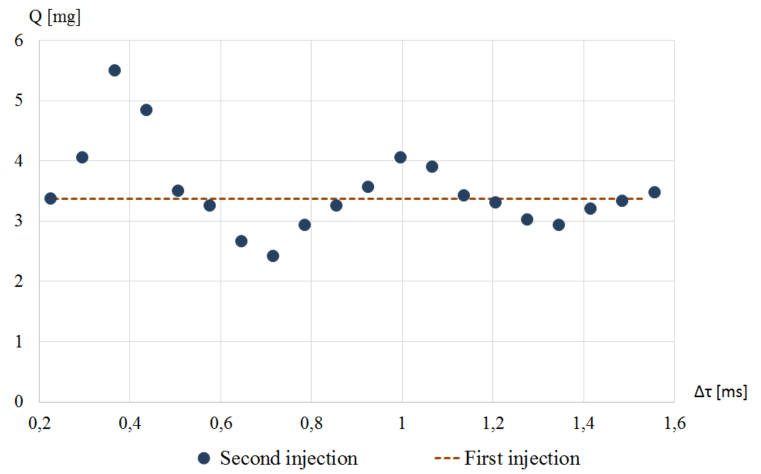

Fig. 17. Fuel injection rate Q_2 at different intervals between injections $\Delta\tau$ for a more dense fuel (Q_1 =3.4 mg): a – p_{ac}=2000 bar, b – p_{ac}=3000 bar

3. The presence of fuel accumulator integrated into the CR injector body decreases wave phenomenon related to fuel injection. During experiments with the injector CRI No2 having an integrated fuel accumulator (p_{ac}=1000 bar, τ_{imp}=0.6 ms), the impulse amplitude at the inlet to the injector was 120 bar which is 3.3 times lower than in the injector CRI No1 having no fuel accumulator.

4. When the fuel accumulator pressure p_{ac} grows, the oscillation phenomenon and its impact on the working process increase. So when operating on diesel fuel at pressure p_{ac}=2000 bar, the spread in injection rates of the second portion is Q_2 = 2.36…4.62 mg, and at p_{ac}=3000 bar Q_2 = 1.58…6.63 mg.

5. When switching to a fuel with a higher viscosity due to the increase of the hydraulic friction there is a more rapid attenuation of the pressure oscillations caused by the preliminary injection. So when injector CRI No1 operates (p_{ac}=1000 bar, τ_{imp}=0.6 ms) on sunflower oil the pressure oscillations range decreases from 40 MPa (operation on diesel fuel) to 25 MPa (operation on sunflower oil).

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Nomenclature

Latin symbols

CRI – common Rail Injector

p_{ac} – rail pressure, [bar]

Q – injection rate, [mg]

Greek symbols

τ_{imp} – time of control impulse, [ms]

$\Delta\tau_{imp}$ – interval between two portions of a double injection, [ms]

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