

Experimental Investigations of the Effects of Electric Control Impulse on Injection Characteristics of Common Rail Type Injector

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Abstract

Background/Objectives: The motor-less fuel stand has been described capturing high-speed video in the process of fuel jet development in Common Rail type injector. **Methods:** The experiments were carried out simultaneously recording the electric signals of the start and end moments of the electrical impulse controlling the injector with digital color oscilloscope Tektronix TDS-2014C and high-speed imaging of the fuel jet sprays with color video camera FASTCAM SA-X2. **Findings:** The delays of the start and termination of actual fuel injection that depend on the electrical impulse for the injector control have been determined and the dynamics of the fuel jet development has been observed under the fuel rail pressure from 100 to 165 MPa. The dependency of the duration of the fuel injection process on the duration of the electrical impulse controlling the injector has been established. **Applications/Improvements:** The results of the study can be used for diesel engine design and commissioning and for improving the shape of the combustion chamber to ensure better carburetion in the cylinder.

Keywords: Axial Deflection of Fuel Flame, Common Rail Type Injector Control, Duration of Electrical Impulse Controlling Injector, Dynamics of Fuel Jet Development, Fuel Injection Process, Motorless Fuel Stand

1. Introduction

Developing the algorithm for controlling the injector in Common Rail type system is the predetermining factor of the efficient operation of a diesel engine. Setting the characteristics for the electric impulse of the injector control system becomes much simpler when using special motor less stands that help analyze the processes of fuel injection and carburetion, investigate constructive and regulating parameters of the elements of the fuel feeding equipment.

There are a number of well-known studies in this area. Thus, several authors¹ have developed conceptual models of the pretreated low-temperature combustion of diesel fuel and have taken images of the fuel jets in the process of the injection. Another group of researchers² has carried out detailed modeling of the fuel injection process having developed the motor less stand for the purpose. The

development of the fuel flame models has been described in several studies.³⁻⁵ The latter works also describe modeling of the processes of cavitations erosion of the injector orifices and of the internal cavity of the spray nozzle.

Modeling the multiphase fuel injection based on the real engine model has been illustrated in a specifically dedicated study⁶.

Experimental investigations of the effects produced by two-stage injection on fuel injection quantity, combustion and emissions in the diesel engine equipped with Common Rail type system have been described in literature⁷ together with the results of the relevant video imaging. The authors have investigated not only the process of injection but also the process of fuel combustion. Similar investigations of the fuel flames have been presented in several works⁸⁻¹⁰.

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In *South Ural State University* the motor less fuel stand equipped with constant volume chamber and with the high-speed video camera has been designed and manufactured. It is meant for the complex investigations of the processes of generating the sprayed fuel jets and for determining the pattern of the fuel distribution over the combustion chamber in diesel engines of different power. The stand has been designed taking into account the existing world practices in the area of modeling¹⁻³ and in the area of the experimental investigations of the processes of injection, spraying, carburetion and combustion of fuel in both motor and motorless stands⁷⁻⁹.

The characteristics of injecting and spraying diesel fuel have been compared with those of other types of fuel in case of one and the same fuel system in a special study¹¹. Similar investigations have been carried out for biodiesel fuel, gasoline, dimethyl ether¹²⁻¹⁴.

Several scientists¹⁵ have undertaken detailed investigations and comparisons of the parameters of the fuel jets of kerosene, diesel and biodiesel fuel in the initial period of its injection into the medium under atmospheric pressure and the parameters that correspond to the real conditions in the cylinder of the engine. A number of the researchers in their works¹⁶ use to simulate the conditions of the environment that are close to the real conditions by applying special liquids of different density. Thereat, the fuel is injected into the relevant liquid medium.

One of the studies¹⁷ defines the effects that are produced by fuel injection on its spraying and distribution over the combustion chamber. The high-speed visualization of the transitional processes of diesel fuel spraying in the course of its injection through multi-nozzle injectors under high pressure made it possible to compare different options under different injection pressure values.

The issues related to the dynamics of the injector needle under different injection pressure values have been described in several studies¹⁸⁻²⁰. The investigations have been carried out assisted by high-speed X-ray imaging for the purposes of studying the processes of fuel cavitations and of the inflow of air into the internal cavity of the spray nozzle.

2. Concept Headings

An important aspect of developing the algorithm for injector control in the course of investigating the injection process is to determine the delays of the start and end of actual fuel injection that depend on the electrical

impulse controlling the injector under different pressure values in the fuel rail together with the dynamics of the fuel sprays development that also depend on this process. However, the attention paid to these issues by the available literary sources is insufficient and the conclusions made are often of contradictory nature. Therefore, the objective of this study is to carry out the experimental investigations aimed at determining the effects produced by the duration of the electric impulse controlling the injector on the delays of the fuel injection start and termination and the actual duration of the injection with Common Rail type injector in order to formulate the required characteristics of the electric impulse for injection control in diesel engine. Thereat, several problems of determining the duration of the electrical impulse for the injector control were solved: duration of the actual fuel injection process; dynamics of changing lengths of the sprayed fuel jets, axial deflection and the basic cone angles of the fuel flames; tangential velocity of vortex air flow under different pressure values in the fuel rail.

The analysis of the studies above made it possible to develop the methods for carrying out the investigations with the motor less testing bench specifically designed for studying diesel engine injectors.

In the course of the investigations the electric signals of the start and termination of the electric impulse for the injector control were registered simultaneously with high-speed video camera and with digital color oscilloscope Tektronix TDS-2014C. The duration of the electric impulse controlling the injector has been preset as 0.5 ms up to 3.0 ms with the pitch of 0.5 ms. Air pressure in the constant volume chamber has been set as 3 MPa at a temperature of 20°C. The initial pressure in the fuel rail was set from 100 MPa to 165 MPa.

In each mode the experiments were carried out cyclically assisted by synchronization controller. The moments of the start and end have been established for the processes as follows: electrical impulse for solenoid injector control, video imaging, digital oscilloscope recording.

Based on the time tag of the oscillogram obtained with oscilloscope Tektronix TDS-2014C the moments of actual beginning $\tau_{\text{man.beg}}$ and end $\tau_{\text{man.end}}$ have been identified together with the duration of the electrical impulse for the injector control $\tau_{\text{man.spr}}$ as the difference between them.

Actual moments of start and termination of solenoid-operated fuel injector have been identified by the results of video imaging and were counted from the beginning

point registered by Tektronix TDS-2014C digital oscilloscope recording. At video speed of 10,000 frames per second the time interval between the consequent frames used to be 0.1 ms. The moment of the injection beginning τ_{beg} was identified as the moment in the video when the first fuel sprays emerged in the spray nozzle orifices. The moment of the injection end τ_{end} was identified as the moment in the video when the fuel ceased flowing from the spray nozzle orifices. The duration of the fuel injection τ_{spr} was determined as difference between the moments of end τ_{end} and start τ_{beg} of the fuel injection process.

The durations of the delays of the injection start $\tau_{del.beg}$ and the injection termination $\tau_{del.end}$ were determined by comparing the time results of the electrical impulse for injector control registered by digital oscilloscope Tektronix TDS-2014C and by video camera FASTCAM SA-X2 with the resulting moments of the captured images of the fuel jets. When the video camera was turned on simultaneously with sending the electrical impulse for injector control, the duration of the injection start delay $\tau_{del.beg}$ was numerically equal to τ_{beg} . The duration of the injection termination delay $\tau_{del.end}$ was determined as the difference between the fuel injection end τ_{end} and the end of the electrical impulse for injector control $\tau_{man.end}$.

3. Results

The schematics of the stand are shown in Figure 1. The motor-less stand is equipped with the systems as follows: Common Rail type fuel feeding equipment with adjustable pressure of 100 to 200 MPa, bottled compressed air feeding system, purging, preheating and gas-air vortex formation systems, high-speed video imaging and stand control systems.

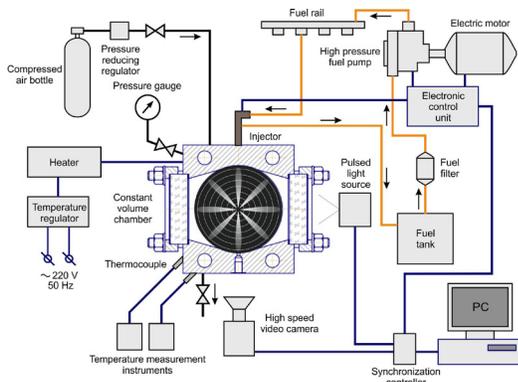


Figure 1. Schematics of motorless fuel stand for investigating the processes of fuel injection and carburetion in constant volume chamber.

The principal element of the stand is represented by universal constant volume chamber designed for pressure up to 10 MPa. The chamber is equipped with three windows made of toughened silica glass for lighting and for high-speed video capturing of the sprayed fuel jets, with the socket for installing Common Rail type fuel injector, with valves for feeding air and for purging purposes and also with the pressure gauge and thermocouple for measuring pressure and temperature.

On both sides of the constant volume chamber the LED lighters of 100 W are installed shown in Figure 2.



Figure 2. Constant volume chamber with LED lights.

The stand control system ensures synchronous single injection of the fuel into the constant volume chamber, switching the high-speed video camera and the registration mode of 4-channel digital oscilloscope.

To obtain the high-speed color video the experiments made use of FASTCAMSA-X2 camera manufactured by Japanese company Photron. The speed of video imaging was preset as 1,000 up to 100,000 frames per second. The examples of the pictures illustrating the development of the fuel jets in the constant volume chamber are shown in Figure 3.

Figure 4 presents the dependencies of the durations of the delays of the injection termination and of the duration of the whole process of fuel injection under different pressure values in the fuel rail p_r on the duration of the electrical impulse controlling injector $\tau_{man.spr}$. With the durations of the electrical impulse controlling the injector $f \tau_{man.spr} \geq 1.0$ ms, the duration of the delay of the injection termination $\tau_{del.end}$ amounted to 1.0 ± 0.2 ms. The duration of the delay of the beginning of the fuel injection $\tau_{del.beg}$ did not change and amounted to circa 0.3 ms.

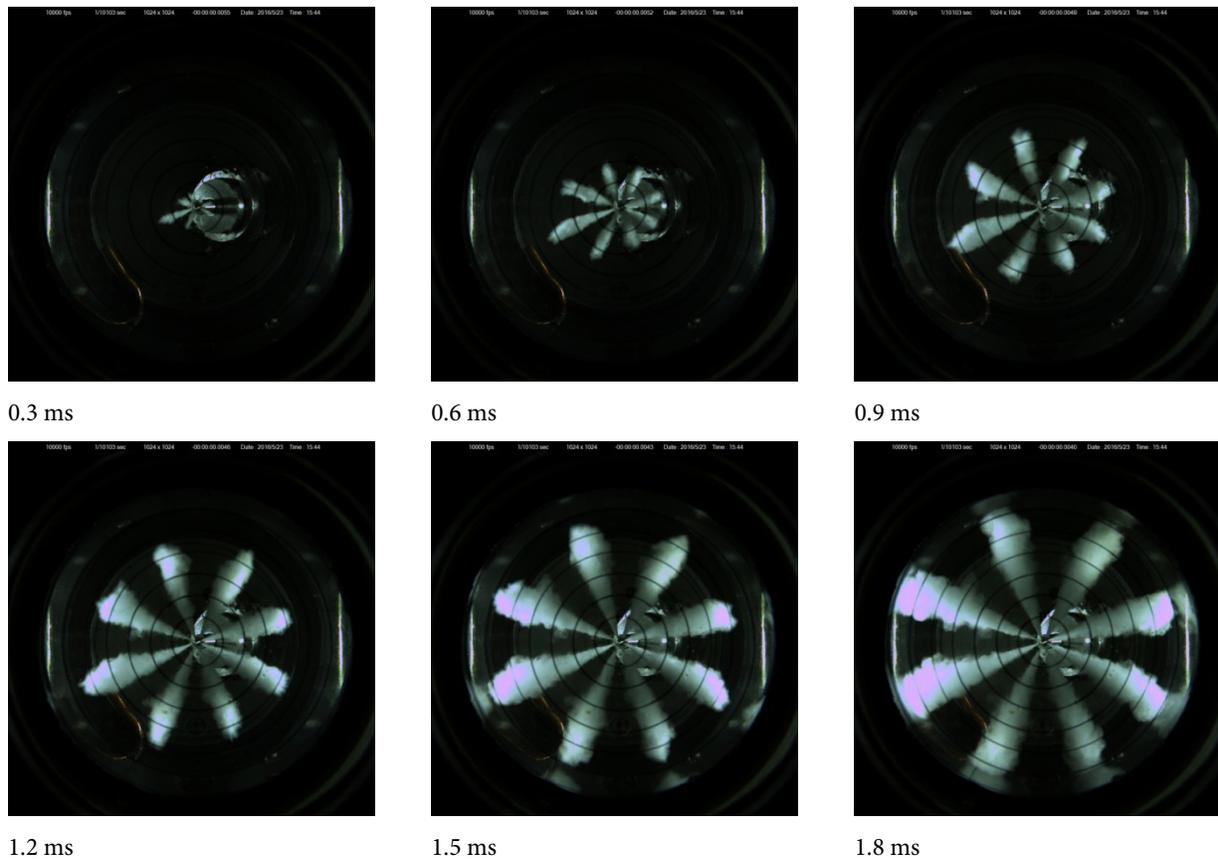


Figure 3. Example photos of fuel jet development in constant volume chamber.

As the duration of the electrical impulse controlling the injector was increasing, so, expectedly, the duration of the whole process of the fuel injection under the given fuel rail pressure values was increasing as well.

The dynamics of changing lengths of the sprayed fuel jets was determined by measuring the lengths of the visible parts of the jets (distances between the sprayer nozzle and the apexes of the visible parts of the fuel jets) based on their images over the time captured during imaging with the high-speed camera. Microscopic imaging of the fuel flame with the high-speed digital video camera made it possible to trace the dynamics of the fuel spaying. Figure 5 presents the graph of the dynamics of changing average lengths of the fuel jets under the fuel rail pressure of 165 MPa built based on the results of processing the pictures from Figure 3. At the initial stage within 0.5 ms the maximal speed of the fuel jet apex was circa 50 m/s, and then it was reduced to ~35 m/s. As a result, the average jet reached the length of 60 mm in 1.7 ms after the start of the control impulse.

The investigations have shown that the duration of the electrical impulse controlling the injector produces no considerable effects on axial deflections of the fuel flames under any investigated fuel rail pressure values from 100 MPa to 165 MPa. The pictures shown in Figure 3 demonstrate that the visible outlines of the fuel flames are not even; they possess local curvatures and differ considerably from the geometrical shape of cone. This can be explained by the turbulent flows at the boundary where the two-phase fuel and air jet comes into contact with compressed air. However, it is a general practice that at a first approximation the shape of the sprayed fuel flame is conventionally represented as a cone. Therefore, the cone angles of the sprayed fuel flames were determined through the middle line of the external surface without taking into account the fluctuations and excluding the head part of the flame. The measured values of the fuel flame cone angles for each mode of investigations and for each particular flame were put into tables. The analysis of the results of the measurements has shown that under the

constant fuel rail pressure and with different durations of the control signal to the injector the values of the flame cone angles remain practically unchanged. As the fuel rail pressure increases from 100 MPa to 165 MPa the flame cone angles decrease by 15% on average.

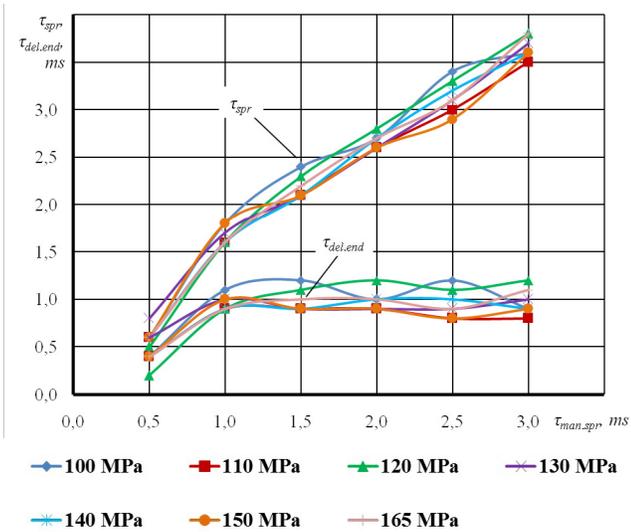


Figure 4. Dependency of fuel injection duration and of injection finish delay on duration of electrical impulse for the injector control.

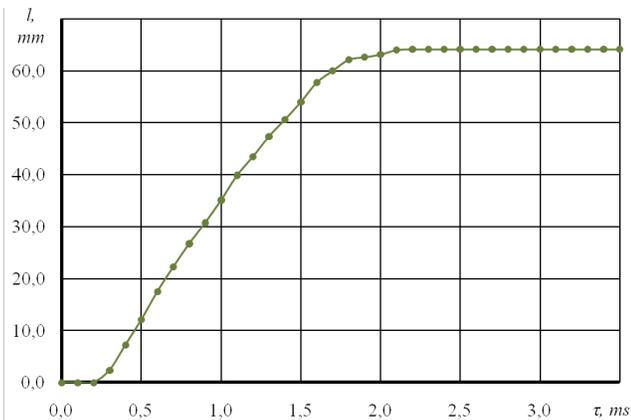


Figure 5. Dynamics of changing average lengths of fuel jets.

This study presents the results of the experimental investigations aimed at determining the effects produced by the duration of the electrical impulse controlling the injector with the air vortex in the constant volume chamber on the range of the sprayed fuel jets and on the deflection of their axes relative to the straight line movements under different pressure values in the fuel rail. The vortex formation and pressure maintenance in the constant volume chamber were insured due to the tan-

gential feed of the compressed air from the bottle through the inlet valve with its simultaneous discharge from the chamber through the outlet valve. Thereat, in the constant volume chamber the dynamic equilibrium of pressure was always maintained due to the fact that the inlet and outlet air flows were equal. Reviewing and analyzing the results of the high-speed video imaging proved that there is no any axial deflection from the straight line of the sprayed fuel jets. The lengths of the fuel flames during air vortex formation practically coincide with the values that have been registered earlier in the course of carrying out the tests with no air vortex formation.

4. Discussion

The experimental investigations have been performed to identify the effects produced by the controlling electric impulse on the characteristics of fuel injection with Common Rail type injector. The developed motorless fuel stand made it possible to carry out the experimental tests assisted by high-speed video imaging of the processes of fuel injection and carburetion in the constant volume chamber. Based on the results of the video images the actual moments of the start and termination of the fuel injection through the solenoid injector under the fuel rail pressure from 100 to 165 MPa and the durations of the electrical impulse controlling the injector from 0.5 to 3.0 ms have been registered. The delays of the start and termination of actual fuel injection and the dynamics of the fuel jet development have been determined. The graphic dependency of the duration of actual fuel injection process on the duration of the electrical impulse controlling the injector has been built.

Based on the dynamics of the changing lengths of the fuel jets, the average velocities of the jet apexes have been found. The duration of the electrical impulse controlling the injector does not produce any considerable effects on the axial deflection and on the values of the flame cone angles under constant pressure value in the fuel rail. As the fuel rail pressure increases from 100 MPa to 165 MPa, the flame cone angles decrease by 15 % on average which can be easily explained.

The lengths of the fuel flames and their axial deflection from the straight line movements in the process of air vortex formation virtually coincide with the values that were recorded at the experiments that featured no air vortex formations. This can be explained by the insufficiency

of the tangential velocity of the vortex air that is fed into the chamber, by the great mass of the air that is located within the chamber and also by large kinetic energy of the fuel that flows from the nozzle orifices of the nozzle sprayer that helps overcome the resistance of air vortex without changing the movement trajectory.

5. Conclusion

The equipment of the stand makes it possible to investigate the effects produced by the parameters of Common Rail fuel feeding system (diameter and the number of spraying orifices, fuel injection pressure, duration of the electrical impulse controlling the injector), parameters of the operating body within the chamber (pressure and temperature), physical properties of the fuel, intensity of air vortex movements in the constant volume chamber and also by other parameters of the dynamics of changing shapes and lengths of the spray jets.

The results of such investigations can be used at the stages of diesel engine design and commissioning for solving the problems of upgrading the shape of the combustion chamber in order to improve the quality of carburetion in the cylinder of the engine to maximize technical, economic and environmental performance.

The study has described the results obtained for just one typical design of the sprayer; however, there will be no difficulties in applying these results to developing the characteristics of Common Rail electrical impulse for the injector control, to developing the algorithm for controlling the fuel feed systems of diesel engines.

The study has not touched upon such important aspects of fuel feeding processes as the effects produced by the duration of the electrical impulse controlling the injector on cyclical fuel feeding. This is because the additional investigations would be required for different typical designs of the sprayers featuring different diameters, different number and arrangement of injector orifices that would inevitably affect the characteristics of the electrical impulse for the injector control.

Upgrading the stand and installing the relevant additional measuring equipment will make it possible to carry out the investigations of the wave phenomena that occur in the pipelines of the fuel feeding systems and also to analyze the effects of hydrodynamic parameters of fuel in the pipelines on the parameters of injection and carburetion.

There are intentions to further develop the investigations in these areas and the existing motorless fuel stand will make it possible to do so.

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