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ANALYSIS OF INJECTORS REACTION ON THE EXTERNAL SIGNALS IN DIRECT INJECTION SYSTEMS

The aim of the research was to assess the external signals of fuel injection by piezoelectric injectors of engines fueled with gasoline and diesel fuel. The assessment focused on the delay analysis of fuel injection start in relation to the time of appropriate control signals occured. The research on these relations was conducted with the use of the system for analysing fast-varying processes and high speed camera HSS 5 by LaVision installed in the test stand with constant-volume chamber. The tests were conducted for different injectors with direct injection of liquid fuels under variable conditions: different fuel pressure, air backpressure and injection time. The paper correlates the electric parameters activating injector operation with parameters of actual fuel injection. For this purpose the digital processing of images was applied enabling actual times determination of fuel injection initiation. Essential differences between the activation time of fuel injection and its actual occurrence were pointed out.

Keywords: fuel injection, injection delay, constant-volume chamber

1. INTRODUCTION

Fuel injection and atomization are fast-varying processes on the quality of which the fuel-air mixture parameters in the combustion chamber depend. Delivery of fuel into the combustion chamber depends on the systems used to enforce fuel flow. The essential parameters of these systems are the fuel injection pressure, injector type and geometry of the injector nozzle. Among the injectors currently used for the direct liquid fuel injection dominate two main designs: electromagnetic and piezoelectric.

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Due to the possibility of gaining shorter opening times, the piezoelectric injectors are the solution replacing electromagnetic designs in the accumulation common rail type systems [Wisłocki et al. 2010].

The tool enabling the analysis of fuel injection process is the constant-volume chamber [Bueschke et al. 2014]. Tests of this type complemented with information on the fuel injected quantity per cycle make it possible to draw conclusions on creating the strategy of supplying fuel to the combustion engines. Precise assessment of the fuel dose without special apparatus is difficult; therefore in literature are two main methods to solve that problem: Zuech and Bosch [Arcoumanis, Baniasad 1993]. All fuel indicators are based on principals mentioned in that publication.

The recent conducted investigations are focusing on spray characteristic and it correlation with exhaust toxic compound emission [Ferrari 2016, Manim 2016, Agarwal 2014]. Other way to use optical methods in research is to evaluate fuel droplets diameter [Azami 2016, Sivakumar 2016, Ventura 2016]. Actually not many researchers undertaking analysis of injectors and injection system hardware. Possibility to improve injection process is available by this analysis type. Investigations presented by A. Ferrari et al. [2016] were undertaking analysis of injection process delay. In this research does not take into account optical methods as a tool to determine delay time. Authors selected optical methods to evaluate injector delay time because this technics has better accuracy to observe start of injection then fuel rate indicators.

2. MOTIVATION FOR UNDERTAKING THE TESTS

The main objective of the research is to determine the value of fuel injection delay and the impact of individual elements responsible for this phenomenon. In the high-pressure fuel injection systems, two types of elements responsible for injection delay can be identified: electric and hydraulic.

For electric delay the system of electric force controlling injection operation is responsible. Determining the speed of the actuator response is essential for precise control of fuel injection time. Delivering fuel into the cylinder at a precisely determined piston position guarantees obtaining the desired fuel distribution in the combustion chamber. Irrespective of the injector design, the data on the voltage rise rate and current are desired as they show the operation potential of the control system. The delay of the electric system itself is insufficient for full assessment of the phenomena defining discrepancies between the desired fuel injection signal and its physical initiation. Therefore the other component of the total injection delay is the time necessary for fuel at a particular pressure to fulfill the channels opened by the actuators of the injector. A typical measurement of fuel pressure needs to be determined before the injector. Such measurement does not guarantee that the pressure drop reflects the actual opening time of the injector defined by fuel flow. Only those two elements combination with conditions prevailing in the combustion chamber enables determination of the delay, which is indispensable for precise control of fuel injection.

For the above mentioned reasons, the authors conducted tests aimed at determining the total fuel injection delay, taking into consideration both, delay of the electric activation and delay of the hydraulic system operation.

3. METHODOLOGY OF RESEARCH

3.1. Tested objects and their characteristics

The tests on the processes of fuel injection delay were conducted with the use of piezoelectric injectors utilized in SI and CI engines, parameters of which are presented, respectively, in Table 1 and Table 2.

Table 1

Technical specification of piezoelectric outward-opening gasoline injector [Achleitner, Bäcker, Funaioli 2007]

Parameter	Value
Dynamic flow	14.5 mg/inj ± 10%
Minimum dynamic flow	< 2 mg/str
Spray angle	90º ± 3º
SMD size	~ 15 μm
Opening/closing time	> 150 μs
Maximum voltage	190 V
System pressure	5–20 MPa

Table 2

Technical specification of piezoelectric diesel fuel injector [Bosch 2016]

Parameter	Value
No. of holes	8
Static flow	705 cm^3/min
Spray angle	162º
System pressure	25–180 MPa

3.2. Description of the test stand

During the research on fuel injection delay, for simulation of conditions prevailing in the cylinder the constant-volume chamber with optical access was used to observe the fuel flow from the injector. The test chamber used enabled obtaining the values of the back-pressure (measured by Keller PA2 SR sensor) of the medium into which the fuel was injected (the injection determined by AVL SL31D-2000 sensor – natural frequency – 50 kHz) similar to the values prevailing in traction engines.

Two 500 Watt halogen lamps (powered by 24 V), placed outside the chamber next to the quartz glass were used to illuminate the fuel. The lamps, in order to obtain the best possible luminance of the image (exposure) were placed in opposition. The injector was placed next to the optical window, enabling optical access. In the system of high fuel pressure, before the injector, the manometer for analyzing fuel pressure was installed. For process recording (apart from the camera) was also used the system for fast-varying signals acquisition – AVL Indiset. It was used for recording the enforcement of an electric signal (5V, TTL) defining the set time of the injector opening (released by a sequencer with resolution ±2 ns). Other values recorded by Indiset system are characteristics of pressure before the injector, signal controlling LED diode activation and characteristics current flowing through the injector (Chauvin Arnoux current clamp designated E3N with measuring set-point of 10 mV/A). The view of the test bench is presented in Fig. 1.

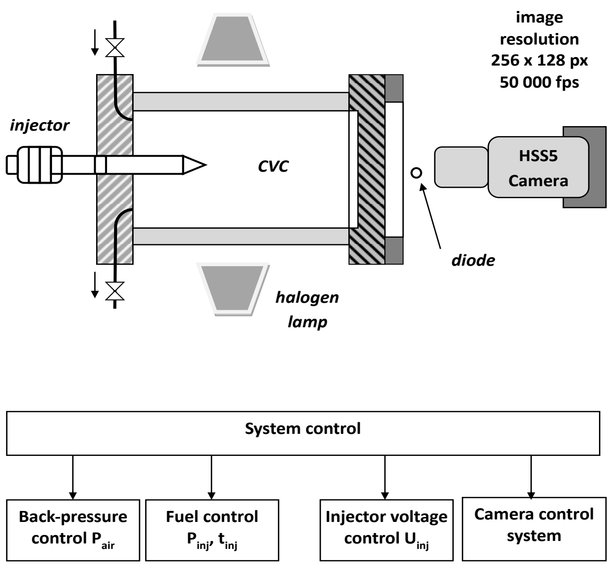

Fig. 1. The test bench for testing the delay of fuel injection

The optical observation was conducted with the use of high speed camera enabling recording of the image sequence with the speed of 50 kHz ($\Delta t = 20$ μs) while maintaining resolution of 256 × 128 pixels.

The tests were conducted in variable operational conditions of gasoline and diesel fuel injectors. The selected test points took into consideration conditions prevailing in the engine combustion chamber. While selecting those points the dependency was followed that large values of the fuel injected pressure should occur for high engine loads and so higher values of fuel pressure correspond to higher values of air pressure (back-pressure). For each tested point the injection pressure – P_{inj} and back-pressure – P_{air} were determined. The measurements were taken in several points for different injection times. The set values of injection systems are presented in Table 3.

Table 3

The conditions of tests on fuel injection delay for piezoelectric injectors

Parameter range	Gasoline	Diesel
P_{inj} [MPa]	5–15	50–130
P_{air} [MPa]	0.5–2	1.5–2.5
t_{inj} [ms]	0.15; 0.2; 0.3; 0.6	0.15; 0.2; 0.3; 0.4

3.3. Methodology of determining the fuel injection delay

Fuel injection delay was determined on the basis of the sequence of actions presented below:

− the external electric signal (5V, TTL signal) activating injector operation, diode activation, pressure before the injector and the characteristics of the current measured by the current clamp were recorded (Fig. 2),

− the electric signal of the diode in optical tests was acquired; diode signal acquisition in the fast-varying and optical tests enables synchronization of both measuring techniques, making it possible to determine the delay time of injector operation taking into consideration electric and optical signals,

− the injector operation delay was determined on the basis of analysis of interval between the external electric 5V signal activating injector operation and diode activation – fast-varying tests (Fig. 2),

− the delay of fuel flow from the injector was determined as the interval between the diode activation and initiation of fuel injection. manometer.

The above-mentioned description suggests that injection delay top is described by the dependency (Eq. 1):

$$t_{op} = t_e + t_d + t_k \tag{1}$$

where:
t_{op} – total injection delay time
t_h – hydraulic injector opening delay time
t_e – electric injector opening time delay
t_d – time between electric injector opening and diode indication

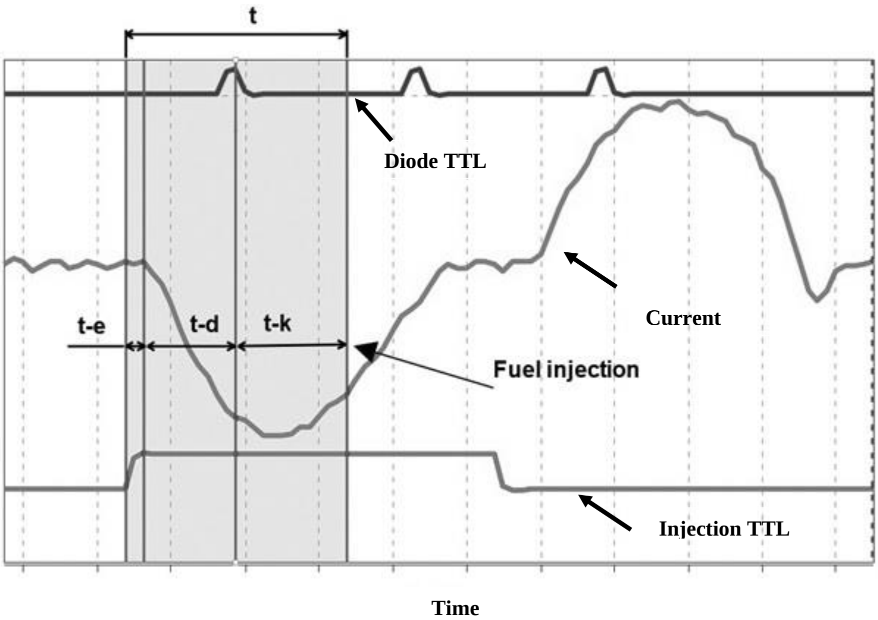

Fig. 2. The analysis of the interval of the injector opening delay: method of recording signals and determination of injection delay t on the basis of electric and optical signals where: t-e – is the time of electric fuel injection delay; t-d – is the time from the electric fuel injection delay to the diode activation time, t-k – is the time from diode activation to occurrence of fuel drops on the injector

The above equation suggests that the time of hydraulic delay of fuel injection can be calculated as the sum of the times, diode activation and time of fuel drops occurrence (Eq. 2):

$$t_h = t_d + t_k \tag{2}$$

4. EXAMPLES OF DEFINING FUEL INJECTION DELAY

The tests on fuel injection delay were conducted with the use of modern piezoelectric injectors for liquid fuels. The examples of sequence and methods to defining the delay between diode activation and the fuel injection start on the basis of optical tests are presented, respectively, in Fig. 3 and Fig. 4. Frames were recorded with time interval of $\Delta t = 20$ μs and thanks to the graphical processing of the images it was possible to obtain information on occurrence of the first fuel drops flowing from the injector nozzle. The beginning of the analyzed section was the moment when the first time diode was activated, which enabled synchronization of data on the recorded current characteristics with recorded images with defined precision. While analyzing the film, attention was focused on the spot, where the nozzle of the injector was. In this area the points were searched with luminance different from the points generated by the injector nozzle without fuel flowing. During the analysis were obtained delays in the operation of gasoline and diesel fuel injectors. The values of which are presented in the following chapter.

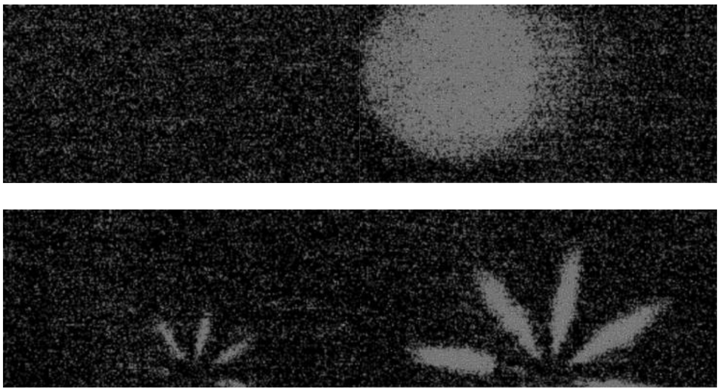

Fig. 3. The sequence of the diode activation and synchronization of the beginning of fuel injecting during the tests of piezoelectric diesel injector (1 – background frame, 2 – frame with diode blink, 3 – starts of fuel flow, 4 – advanced stage of fuel sprays)

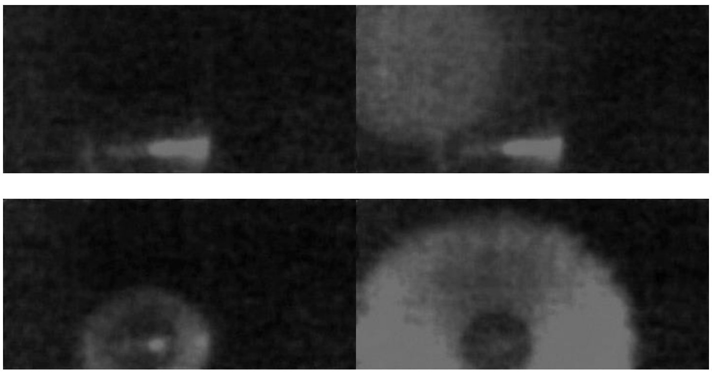

Fig. 4. The sequence of the diode activation and it synchronization with the fuel injection start during the tests of piezoelectric gasoline fuel injector (1 – background frame, 2 – frame with diode blink, 3 – starts of fuel flow, 4 – advanced stage of fuel stream)

5. THE ANALYSIS OF THE FUEL INJECTION DELAY FOR GASOLINE INJECTORS

The obtained measurement results were divided into particular components and a detailed analysis of those measurements is presented in Figs 5–7. During the direct injection of gasoline the longest delays were obtained for minor loads (Fig. 5). The delay values of electric signal are insignificant (ranging from 10 μs to 15 μs), due to which the differences between the measured values amount to 33%. That influences insignificantly the total time of electric delay, invariable for all the measuring points.

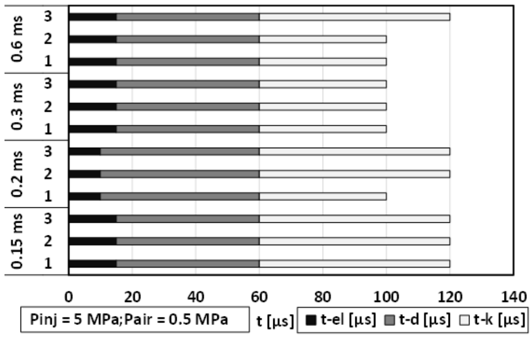

Fig. 5. The values of the component gasoline injection delay times depending on the value of injection time at P_{inj} = 5 MPa, P_{air} = 0.5 MPa

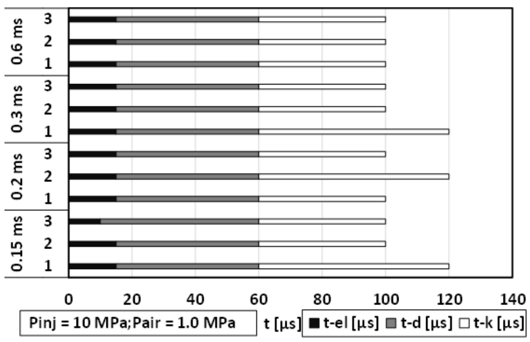

Fig. 6. The values of the component gasoline injection delay times depending on the value of injection time at P_{inj} = 10 MPa, P_{air} = 1.0 MPa

However, the changes of the hydraulic delay are significant and the differences between measurements during gasoline injection amount to 20%, while the range of the delay is 7 to 8 times bigger compared to electric delay.

For the apparatus set for P_{inj} = 10 MPa (Fig. 6) and P_{inj} = 15 MPa (Fig. 7), the same values of electric delay were obtained. While analyzing the results it was observed that the least values of hydraulic delay were obtained for the highest values of set-points simulating loads of the combustion engine (Fig. 7).

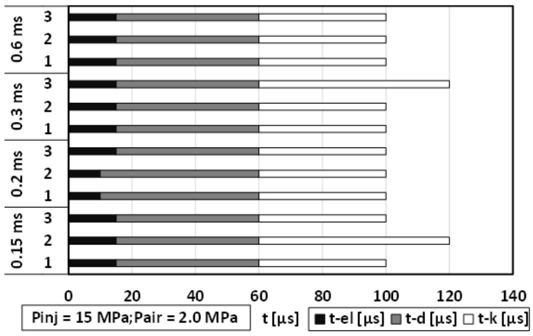

Fig. 7. The values of the component gasoline injection delay times depending on the value of injection time at P_{inj} = 15 MPa, P_{air} = 2.0 MPa

In the following chapter the analogous results of tests concerning diesel fuel injection are presented.

6. THE ANALYSIS OF THE DELAY OF FUEL INJECTION FOR DIESEL FUEL INJECTORS

Similarly to the results obtained for gasoline injectors, also the analysis of measurements for diesel fuel injectors was conducted. The results are presented in Figs 8–10. The times of electric delay for fuel injection oscillate within the same range as in

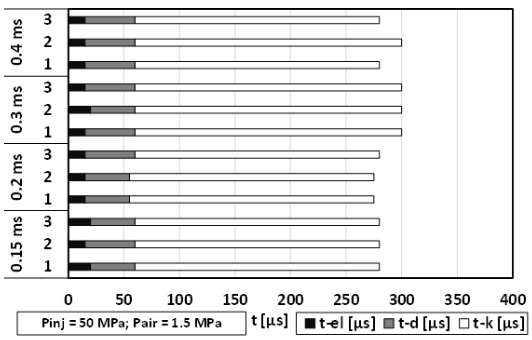

Fig. 8. The values of the component diesel fuel injection delay times depending on the value of injection time at P_{inj} = 50 MPa, P_{air} = 1.5 MPa

case of gasoline injection delay, and amount to approximately 60 µs irrespectively of the value of fuel pressure. However, the values of hydraulic injection delay are several times bigger – and amount to over 200 µs; the total delay is more than twice as big as in case of gasoline injectors operation. Additionally, for P_{inj} = 130 MPa and P_{air} = 2.5 MPa, lower values of set-points resulted in lack of diesel fuel injection (Fig. 10).

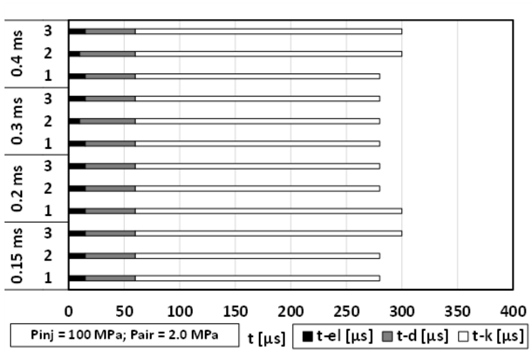

Fig. 9. The values of the component diesel fuel injection delay times depending on the value of injection time at P_{inj} = 100 MPa, P_{air} = 2.0 MPa

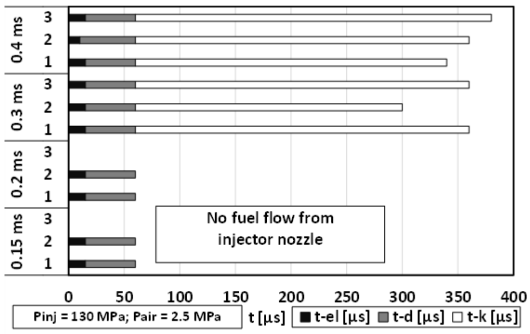

Fig. 10. The values of the component diesel fuel injection delay times depending on the value of injection time at P_{inj} = 130 MPa, P_{air} = 2.5 MPa

7. CONCLUSIONS

A precise control of the liquid fuel injectors requires not only expertise in the injecting systems, but also information about the delays in the process. That statement was proven on the basis of the conducted tests. It was indicated that apart from significant influence of the delays on the injectors control. It is additionally variable depending on the operating parameters of such a system. The following dependency was indicated: high gasoline injection delay corresponds to low injection pressures and low back-pressure of the air. On the other hand, for diesel fuel injector operation the tendency is quite the opposite: with the increase of fuel injection pressure and back-pressure of the air, the delay between the external signal and physical occurrence of the fuel on the injector increases.

The summary of those tests indicates the share of hydraulic and electric delays – Fig. 11 and 12. Despite the fact that the electric delay of the gasoline and diesel fuel injectors lies within the same range, its share in relation to the hydraulic delay is twice less important for diesel fuel injectors compared to gasoline injectors. The presented analysis also shows that the hydraulic delay has 86–96% participation in the total delay of the injectors operation.

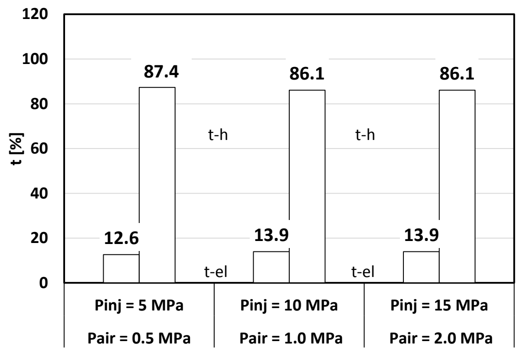

Fig. 11. The values of the component gasoline fuel injection delay times depending on the value of injection time at P_{inj} = 130 MPa, P_{air} = 2.5 MPa

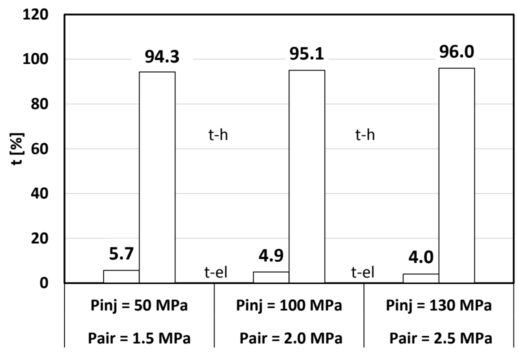

Fig. 12. The values of the component diesel fuel injection delay times depending on the value of injection time at P_{inj} = 130 MPa, P_{air} = 2.5 MPa

In Figure 13a are presented the averaged values of particular components for gasoline injector, irrespective of the injection time. The fuel pressure and conditions prevailing in the pressure chamber are the variables here. On the diagram a tendency was indicated for reduction of the delay with the increasing values of fuel injection pressure and back-pressure of the medium into which fuel is being injected – which corresponds to the increase of the combustion engine load.

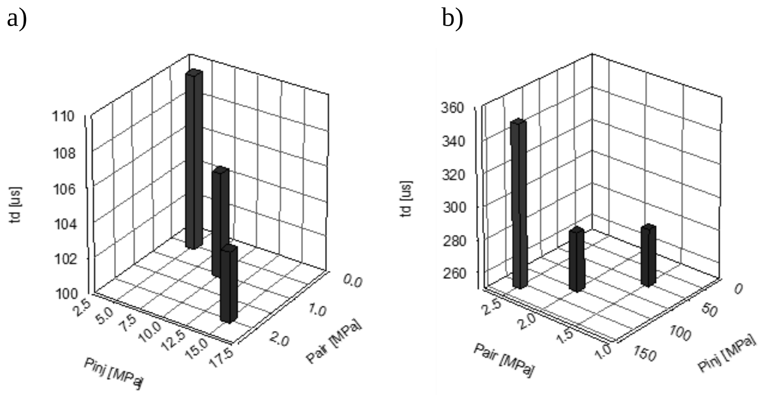

Fig. 13. The overall delay injection trends for piezoinjectors: a) gasoline, b) diesel

The assessment of the mean values indicates a limited hydraulic delay time with increasing fuel injection pressure and invariable time of electric delay in operation of the injector.

Similarly as for gasoline injection, the results of analysis irrespective of the diesel fuel injection time are presented – Fig. 13b. During diesel fuel injection, the tendency in the delay changes of the system operation is different from that observed during the tests for gasoline injection delay. For relatively small values of fuel pressure and air back-pressure, the values of the delays are similar, but an increase in the injection pressure and back-pressure of the air lengthens the time of the hydraulic delay.

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ANALIZA REAKCJI WTRYSKIWACZA NA SYGNAŁY ZEWNĘTRZNE W UKŁADACH WTRYSKU BEZPOŚREDNIEGO

Streszczenie

Celem artykułu było oszacowanie wpływu sygnałów elektrycznych na warunki pracy wtryskiwaczy piezoelektrycznych w układach bezpośredniego wtrysku benzyny i oleju napędowego. Analizę skupiono na opóźnieniu odpowiedzi układu w odniesieniu do pojawienia się sygnału sterującego. Do badań wykorzystano aparaturę do rejestracji przebiegów szybkozmiennych i szybką kamerę do robienia zdjęć HSS5 firmy LaVision. Badania wykonano w komorze stałej objętości przy zmiennych warunkach ciśnienia wtrysku, przeciwciśnienia oraz czasu wtrysku. W artykule powiązano sygnały elektryczne z faktycznym pojawieniem się kropel paliwa w komorze. Do tego celu wykorzystano komputerowo analizowane obrazy. Wskazano różnicę czasu między pojawieniem się sygnału sterującego a rzeczywistym wypływem paliwa.

Słowa kluczowe: wtrysk bezpośredni, opóźnienie wtrysku, komora stałej objętości