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Transient states analysis of CI engine injectors with the use of optical methods

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Abstract. The main aim of research was to define real injection time delay against the time of electrical control signal for piezoelectric and electromagnetic diesel fuel injectors. The second objective of this work was the evaluation of influence of typical injection parameters on this delay. The analysis was focused on the occurrence of appropriate control signals recorded with the use of fast-varying data acquisition system and compared with the data recorded by high speed camera. The tests were conducted in constant volume chamber for different injector types used in combustion engines with direct injection of diesel fuel. The tests were performed under variable conditions: different fuel pressure, air back-pressure and injection duration time.

1. Introduction

High pressure injection of liquid fuel realized by common rail system requires high precision in fuel quantity delivered into combustion chamber by injector. Currently there are two main types of injectors commonly used for both compression ignition and spark ignition engine: electromagnetic and piezoelectric. Although operational fuel pressure in gasoline injection systems is much lower in comparison to diesel fuel systems, but injector opening times are almost the same for both types of construction. That fact makes the requirements similar for CI and SI injectors. These devices should be characterized by possibly fast response to proper control signals for both opening and closing operation. Payri et al. [1] investigated the influence of the electromagnetic and piezoelectric technologies on injection process for indirect-acting piezoelectric and solenoid injectors. In that aspect hydraulic characteristics were prepared for both designs and then compared with each other. In this research the fuel rate indicator based on Bosch method was applied. The achieved results showed faster actuation of piezo-injectors compared the solenoid ones. What it means is that their hydraulic delay is smaller. The differences were increasing inversely proportional to the injection pressure. Second observation from that test was the higher flow speed of fuel for piezo-injector compared to the other design with similar hole diameter.

Similar research was conducted by Yu et al. [2], but in that case fuels selected for investigations were kerosene and diesel fuel. Based only on control signals and variation of fuel flow rate from injector nozzle, the injection delay against the time of electrical opening signal was obtained. The values of this parameter were constant independently of injection pressure (in this case 60 and 100 MPa) and the delay times were respectively 0.45 ms for piezo- and 0.55 ms for solenoid injector. Additionally, faster flow from injector nozzle for lower injection pressures was observed. That fact gives significant benefits to combustion engine operation such as better atomization and evaporation of fuel. The said authors used

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optical methods only to evaluate the rate of fuel spray development during injection but they did not use these methods to estimate the hydraulic delay of fuel injection.
Salvador et al. [3] determined injection delay as a difference between the start of injector energizing and start of fuel spray outflow from injector, which was measured in diagnostic system for estimation of fuel flow rate. This research was conducted for injection pressure range 30—180 MPa and for different fuel temperatures. The results obtained indicated the influence of both parameters on the injection delay. Shorter delay time was confirmed for higher fuel temperature and pressure.
Similar results were obtained by Armas et al. [4]. In fuel pressure range 40—120 MPa and for time of energizing of 0.5—2 ms obtained injection delay was contained within the range of 0.2—0.3 ms. Lower values were reached for piezo-injectors, however while the energizing time was increasing, the delay time was equalizing to the same value—of around 0.25 ms—for both injector types. The optical tests of piezoelectric injectors were conducted by Magno et al. [5] but those tests referred to the influence of injector wear on fuel flow rate. They proved that brand-new injector had a faster response then the used one. The used injector had also different profile of the divided fuel dose: a bigger pilot and smaller main dose. The injection delay against the start of electrical opening impulse was not analysed in this research.
Some prototypes of direct acting piezoelectric injector were presented by Delphi [6] and Continental [7]. The study on these designs was focused on the influence of voltage on fuel flow rate [3, 8, 9]. Payri et al. [9] in their studies used a prototype injector with different rate-shaping models to evaluate the compression ignition indexes of diesel fuel.
Literature studies carried out in the framework of this work have shown that the available knowledge and explanations of the injector control in the aspect of injection delay and its influence on the spray development is insufficient. There are some works available focusing on electrical parameters of control signals and hydraulic parameters for piezo- and solenoid injectors. However, there are no studies focusing on optical investigations in the aspect of injection delay where both electrical delay and hydraulic delay were combined. The authors have already made some preliminary studies in that field [10]. For optical observations the recording speed of 50 kfps was used. In this paper some additional results are presented with accuracy improved by enhancing recording speed up to 250 kfps and for both types of injectors used in CI engines.

2. The research problem

The tests conducted are mainly focused on hydraulic delay and are based on determination of fuel outflow rate from the injector. However, such studies don't deliver enough data to define precisely the start of injection. Unfortunately, the methods are not sensitive enough to record pressure increase in the research chamber from the very beginning. Free of that disadvantage are the optical methods, the application of which allows observing the occurrence of the first fuel drops flowing from the injector nozzle. For that reason the authors decided to use the optical observation of fuel spray creation for their studies on injection delay.
The main research problems of these studies were:

1) determination of the time delay of electrical signal against starting impulse of the process,
2) defining the hydraulic delay of fuel spray creation after starting impulse of the process which can be determined with recording speed of up to 250 kfps.

The methodology applied in this research is presented below in chapter 3.

3. Research methodology

3.1. Test stand

The research was conducted on the test bench in the Institute of Combustion Engines and Transport of Poznan University of Technology. This test bench consists of (its scheme is shown in figure 1):

- A Constant Volume Chamber (CVC) for simulating in-cylinder conditions (back-pressure) typical for injection in internal combustion engine; air pressure range was kept up to 10 MPa; the chamber has optical access and two 500 W halogen lamps to illuminate fuel drops.

- A sequencer to generate control signals (5 V, TTL) for the injection system and the signals powering the diode; resolution of this device is ±1 ns.
- A common rail stand for fuel supply; it consists of high pressure fuel pump Bosch CP 4.1, a control system to achieve fuel pressure in rail up to 200 MPa and another control unit to transform signals from the sequencer into proper electric signal for the injectors to start and finish the injection process.
- Current clamps (Chauvin Arnoux E3N with measuring resolution of 10 mV/A) and passive high-impedance oscilloscope probe M007 by Pico Technology. Both were used to measure electrical signals before the injector.
- An acquisition system which consists of two main elements: the first one is AVL IndiModul to record electric signals (measured by the clamps and the probe) and control signals from the sequencer; the resolution of 500 kHz for signals during this test was selected; the other element is the high speed camera HSS5 by LaVision with recording speed of 250 kfps.

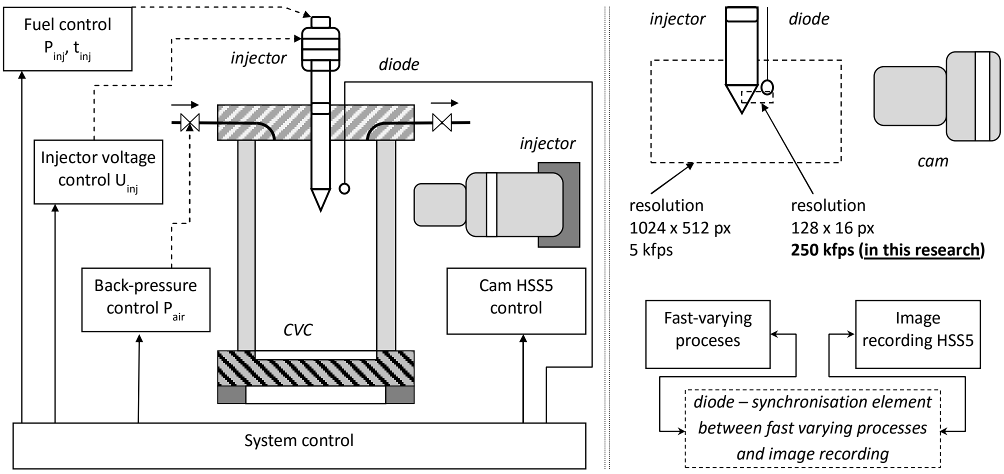

Figure 1. Research stand.

3.2. *Test objects and measuring range*

For the tests the two common-rail injectors of different types were chosen. The first one was a piezoelectric injector by Bosch and the other one was of electromagnetic type, also by Bosch (their parameters are shown in table 1).

Table 1. Characteristics of the injectors.

Parameter	Injector type:	Electromagnetic	Piezoelectric
Static flow		520 cm^3/min	705 cm^3/min
Spray angle		162 deg	170 deg
No. of holes		9	8
Injection pressure		25—180 MPa	up to 200 MPa

The investigations were conducted for values of parameters typical for normal operation of internal combustion engine. The research plan was created with the aim to determine the influence of each parameter on the injection delay time. As the variables of the process were chosen: the injection pressure, the back-pressure and the injection duration. It should be noticed that the last parameter has to get higher value for solenoid injector because of lower fuel flow rate. The range of parameters variation is shown in table 2.

Table 2. Points of measurements.

Parameter	Value
Injection pressure	30—120 MPa; ΔP = 30 MPa
Back-pressure in CVC	2.5—4 MPa; ΔP = 0.5 MPa
Injection duration	0.2; 0.4; 0.6 for piezo-injector 0.3; 0;5; 0.7; for solenoid injector
No. of iterations	2 for each point

3.3. Electrical signal analysis
During the tests, the electric parameters were recorded (figure 2). This data was used to determine the time delay between the starting impulse and the proper electrical signal (measured in the injector with the use of AVL Concerto software). The starting impulse was selected as the start of TTL control signal for the injector; the finish point of this analysis was set as the time when the response on current clamps was observed. The difference between those two points was signed as *t-e* and describes the hardware delay in the injection system. In this analysis the time *t-d* was defined as the time from the start of the impulse (for injector) to the diode response. The meaning of this time will be explained further in this chapter.

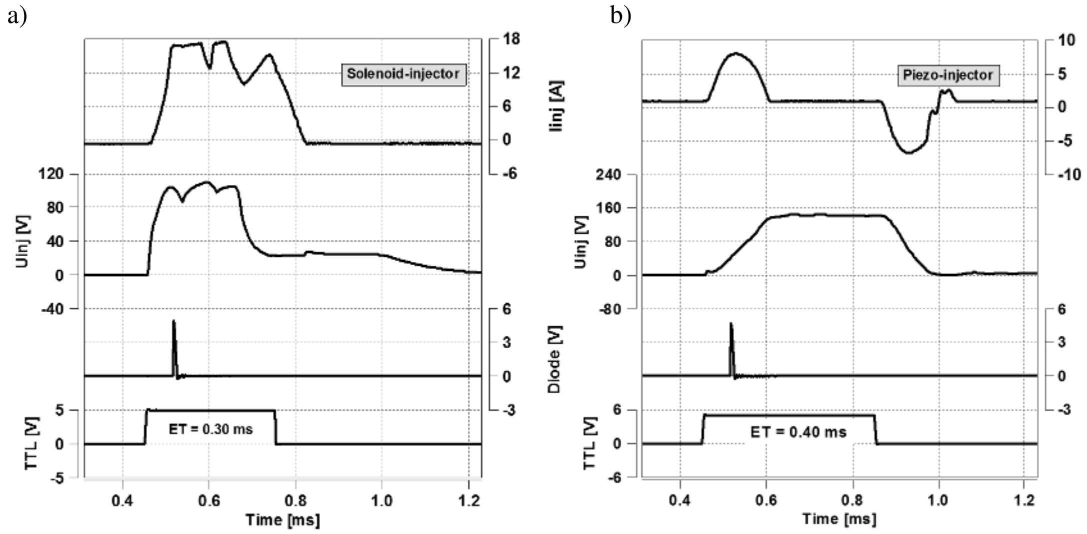

Figure 2. Electric parameters recorded during injector operation:
a) solenoid injector – P_{inj} = 30 MPa, P_{back} = 25 bar, ET (energized time) = 0.3 ms,
b) piezo-injector – P_{inj} = 30 MPa, P_{back} = 25 bar, ET = 0.4 ms.

3.4. Analysis of optical tests
Pictures from optical tests were analysed with the usage of DaVis software from LaVision. The methodology of picture analysis is explained in figure 3. The recording speed was set on 250 kfps with the spatial resolution of 128 × 16 pixels.

At the beginning, the background was subtracted from the raw images to achieve a clear picture of the fuel spray development. The first picture analysed to determine the injection delay was the picture with a diode visible on left side (third photo in figure 3). The diode flash time was set at the value of 4 µs, so it was possible to observe the diode on one frame only. The next step of the analysis was to find the frame where the pixels near the injector nozzle changed their illumination level. The change in illumination means occurrence of fuel drops. That time was described as *t-o*.

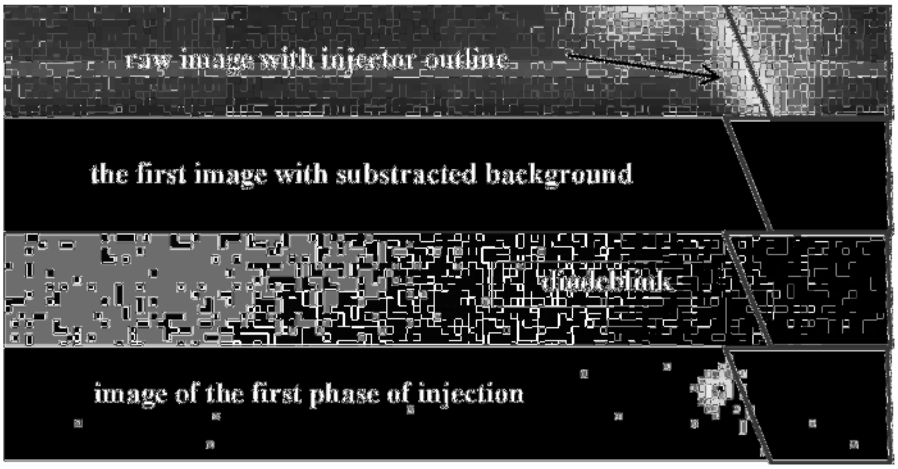

Figure 3. Optical research algorithm of fuel injection based on data from solenoid injector: ET = 0.5 ms, P_{inj} = 120 MPa, P_{back} = 40 MPa.

3.5. Determination of the injection delay

The total delay time from the input signal to the beginning of the injection was defined here as the time difference between the time of the electrical signal from sequencer starting the energizing process and the time of the image with first fuel droplets occurring in the injector nozzle. The diode was used only to synchronize the results achieved from camera and from IndiModule; it reflects the resolution of one recorded frame. In this way, the calculation of fuel injection delay consists of the two main parts (equation 1): electrical and hydraulic delays. As the electric delay the authors understand the value of *t-e* presented in chapter 3.3 (figure 2) and it describes only the delay of the hardware. The hydraulic part (*t-h*, equation 2) consists of *t-d* described in chapter 3.3 and of *t-o* described in chapter 3.4. The hydraulic delay time describes mainly the injector and less the physical parameters of the fuel, such as e.g. viscosity. Equation 1 shows the total delay time according to the presented methodology:

$$t = t\text{-}e + t\text{-}h \quad (1)$$

$$t\text{-}h = t\text{-}d + t\text{-}o \quad (2)$$

The above equations are illustrated in figure 4, whose specific characteristics of the recorded parameters were generated in AVL Concerto. Vertical lines in the figure 4 were assigned to proper frames on the basis of the optical tests.

4. Investigation of the results for piezo- and solenoid injectors

The research results were gathered into groups and presented in form of the charts. The demanded injection time was selected as constant. The results are presented in 3 groups: for short, medium and for long injection time. This type of presentation allows comparing the influence of each parameter on the fuel injection delay. For both injectors the hardware response delay is considered as constant and it is 0.012 ms for piezo- and 0.016 for solenoid injector. As the diode light signal occurs on the same frame after the start of each measurement, it could be stated that the measurements are stable and repeatable.

Figure 5 presents short energizing time for both types of injectors, as was already mentioned in the research methodology. This time amounts to 0.2 ms and 0.3 ms for piezo- and solenoid injector, respectively. On the chart for piezo-injector, the trend to speed up the injection with higher pressure in the chamber was presented. Only for P_{inj} = 60 MPa this tendency is different, but it could be influenced by random circumstances.

The solenoid injector was working in a more repeatable manner and the back-pressure did not make any significant difference in the delay time. In that case the injection pressure was the factor which speeded up the injection, as it was already observed for piezo-injector. What's worth mentioning is the fact, that the results for solenoid injector from P_{inj} over 60 MPa in most cases differ by ±1 frame only, so in terms of the measurement accuracy they should be treated as no difference. Piezo-injector at low injection pressures obtained lower delay than electro-injector, but with the increase in pressure that was reversed. It should be noted that a piezo-injector is an older design: the electromagnetic injector replaced the piezo-injector in the manufacturer designs.

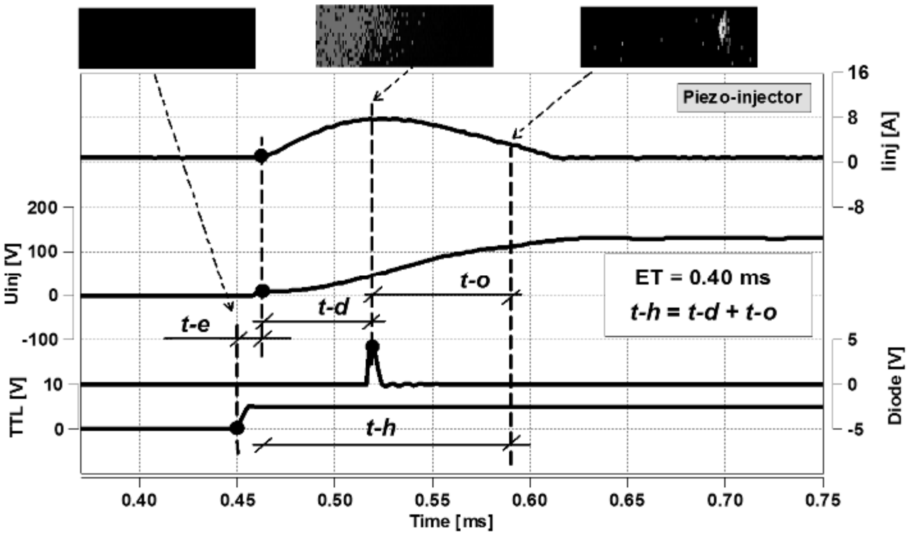

Figure 4. Determination of injector opening delay time based on the recorded data.

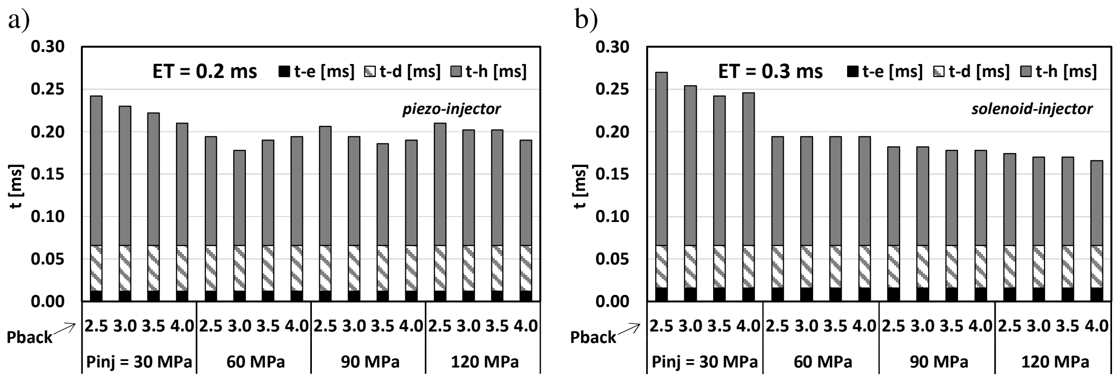

Figure 5. Injection delay for short injection duration; a) piezo-injector, b) solenoid injector.

The results of the injection delay for medium and long injection durations are presented in figure 6 and figure 7, respectively. The piezo-injector operation could be evaluated as more random. On the basis of the results comparison it could be stated, that air pressure (back-pressure) has most significant influence on the delay and the influence of fuel pressure is marginal. Very similar results were achieved for solenoid injectors, but in this case the greatest influence on the injection delay had the fuel pressure and the influence of air pressure was negligible.

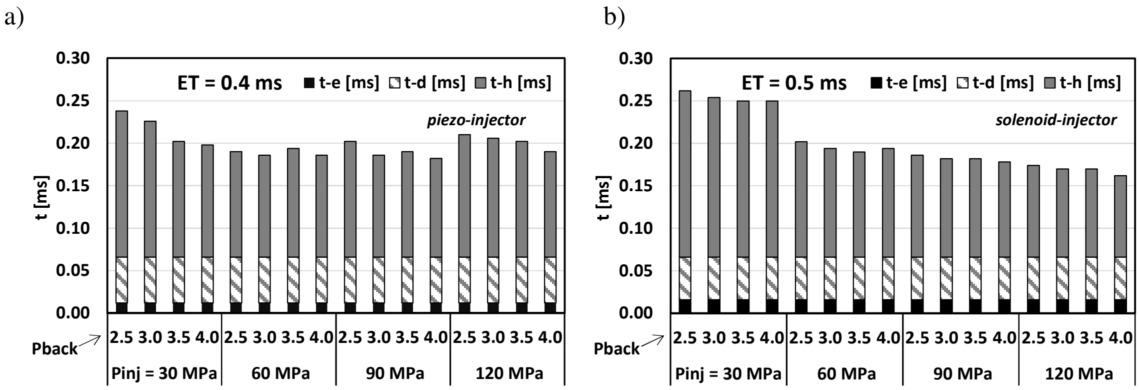

Figure 6. Injection delay for medium injection duration; a) piezo-injector, b) solenoid injector.

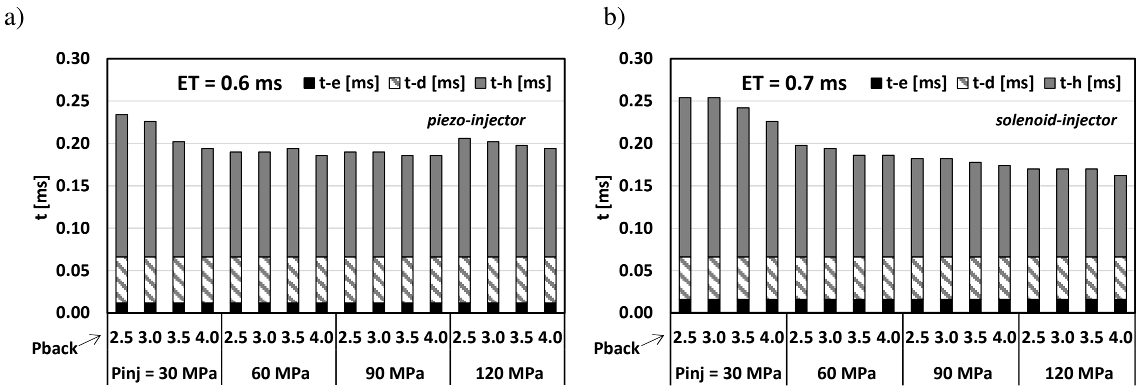

Figure 7. Injection delay for long injection duration; a) piezoinjector, b) solenoid injector.

The above presented results show that these two types of injectors have different properties in terms of their reaction on the electrical opening signal. The piezo-injector is more sensitive to the back-pressure and the fuel pressure has marginal impact on its performance. A contrary situation is noticed for solenoid injector – the biggest impact on the injection delay has the injection pressure. Smaller, but still noticeable impact on this parameter was observed for back-pressure. The injection duration has no impact on the injection delay. According to electrical signals charts such conclusion is correct: the signal from the sequencer continued when the drops of fuel occurred (so if the amplification caused by the appearance of the signal occurred, it lasted for all the measuring points).

5. Summary

In this paper, the study on time delay between the electrical signal for the start of the injection and the beginning of the fuel outflow from the injector nozzle were performed and described. For that purpose the measuring system for electrical signals recording of the injector energizing device was implemented and synchronized with optical observations recorded with the use of high speed camera. The use of the light impulse from the diode made it possible to synchronize all recorded data and to determine electric and hydraulic injection delays on this basis.

The comparison of two injector types was performed in conditions typical for normal operation of an internal combustion engine. In the above conditions, the injection delay time was determined as 0.17—0.24 ms for piezoelectric injectors and as 0.16—0.26 ms for solenoid injectors.

The analysis of these tests allows drawing the following conclusions:

a) Electric delay is constant regardless the injector type and its impact on total delay time is marginal; this parameter describes only the hardware system which controls the injection process.
b) Hydraulic delay is much more variable and it depends on the injection process conditions such as back-pressure and injection pressure; the piezoelectric injector demonstrated more sensitivity to the back-pressure; the reaction time of the solenoid injector was mainly dependent on the fuel injection pressure and less dependent of the air back-pressure.

The total delay time obtained during these tests indicates that solenoid injector seems to be faster than the piezo-injector. Additionally, the solenoid type of injectors offers the possibility to control the injection process more precisely. However, this research does not include fuel dose division, where also the closing time delay is crucial. Further investigations should consider these aspects for better understanding of the injection control process.

Symbols and abbreviations

CI	compressed ignition engine
CVC	Constant Volume Chamber
fps	frames per second
HSS	High Speed Star (cam)
I_{inj}	injector current
P_{air}, P_{back}	back pressure
P_{inj}	injection pressure
SI	spark ignition engine
t	time (overall)
t_{inj}, ET	injection duration, energizing time
$t\text{-}d$	time from beginning point to diode power supply signal starts
$t\text{-}e$	electric delay
$t\text{-}h$	hydraulic delay
$t\text{-}o$	time from diode to fuel drops occur
TTL	transistor-transistor-logic
$\underline{U}_{inj}$	injector voltage
ΔP	delta pressure

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