The Qualitative Spray Characteristics of High-Pressure Gasoline Injection System

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Abstract
The paper discusses the analysis of gasoline atomization generated by piezoelectric fuel injectors operating in a high pressure direct injection system. The methodology and tests results of the influence of the fuel injection pressure and combustion chamber back pressure on the changes of the fuel spray geometrical parameters during the injection and on the values characterizing the injection quality have been presented in the paper. The tests were performed for several values of the air back pressure (0.5 and 1.0 MPa) at the injection pressures of 20 and 25 MPa. The following comparative indexes were analyzed: linear and radial spray penetration during the injection. The paper presents also influence of fuel pressure on the uncontrolled 'post injection' effect.

Introduction

The high pressure injection common for CI (compressed ignition) engines has even more dominant role in the preparation of the mixture in SI (spark ignition) engines [8]. The multipulse injection is being applied in the SI engines as well. Due to pressure values of the injected fuel – gasoline (at present approx. 20 MPa), the injection duration is similar to the injection duration of diesel oil. Similarly to CI engines, piezoelectric fuel injectors are beginning to dominate in SI engines (Table 1), in which, however, the injected fuel spray has a different character and different geometrical indexes and fuel flows out of the injector along the spray cone. The most significant injection indexes include the axial and radial penetration of the spray, the area of the spray cone, velocity of the spray distribution and evenness of the spray penetration as well as velocity of the spray along the circumference of the spray cone.

In order to select appropriate injectors for the combustion system, it is necessary to know the characteristics of the fuel injection and the relations between the basic geometrical parameters of the spray and the basic parameters of the injection nozzle as well as the basic control values of such parameters as injection pressure, back-pressure in the research chamber and the injection duration. The research served for determination of the relations for a typical penetration of operation of a high pressure gasoline injector.

The investigations into the fuel injection and its atomization were carried out for typical spark ignition cylinder pressures. The injection pressures were adapted to the contemporary piezoelectric injector design.

Current research on gasoline atomization focuses on high pressure single [3, 9] and multi hole [1, 7] injectors. The said investigations do not concentrate on the issue of gasoline 'post injection'. In the investigations with the use of outward-opening injectors [2, 5, 8, 10] the phenomenon of 'post injection' has not been investigated either.

Table 1. Direct fuel injection for SI engines (various injector types and fuel pressures) [5, 6]

No.	Engine-type	Injector	Injection pressure
1.	BMW HPI	Piezoelectric	20 MPa
2.	Mercedes-Benz CGI	Piezoelectric	20 MPa
3.	Volkswagen FSI	Electromagnetic	3-11 MPa
4.	Mitsubishi GDI	Electromagnetic	5 MPa
5.	Renault IDE	Electromagnetic	10 MPa
6.	Toyota D-4	Electromagnetic	4-13 MPa

Research objects. The results of the investigations of the piezoelectrically controlled gasoline injector of type HPI (high-pressure injection) applied in the SI engines BMW have been presented in the paper. Injectors of this kind deliver cone-shape fuel sprays which can be described by the axial and radial spray velocities and its time resolved distribution.

Test facility. The test-stand (Fig. 1) incorporated the high-pressure gasoline injection system (outwardly opening injector) equipped with the high-pressure and feeding pumps. The piezoelectrically controlled gasoline

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injector was placed in the closed chamber with the controlled back-pressure in the range 0-1.0 MPa. Positioning of the injector allows recording of images of injection course from the side (for the analysis of axial fuel spray penetration) and from the bottom of the spray (for the observations of radial spray penetration).

Research equipment. In the research a high-speed camera, namely High Speed Star 5 manufactured by LaVision [4] and equipped with a CMOS (Complementary Metal Oxide Semiconductor) monochromatic image converter has been used. The recording speed was limited to 3000 frames per second (FPS, time resolution 100 μs) in order to obtain maximum image resolution of 1024 × 1024 pixels (pixel size of 17 × 17 μm). The camera operated in the spectral wave length of λ = 380-800 nm.

A so-called sequencer – a computer device generating particular control signals to the actuators (electromagnetic valves) – was used for the system operation control. It facilitated control of operation of several elements of the research system such as opening of supply and exhaust of control air (under the piston), opening of the gas supply valve, release of electrical impulse in the spark plug and completion of the recording process.

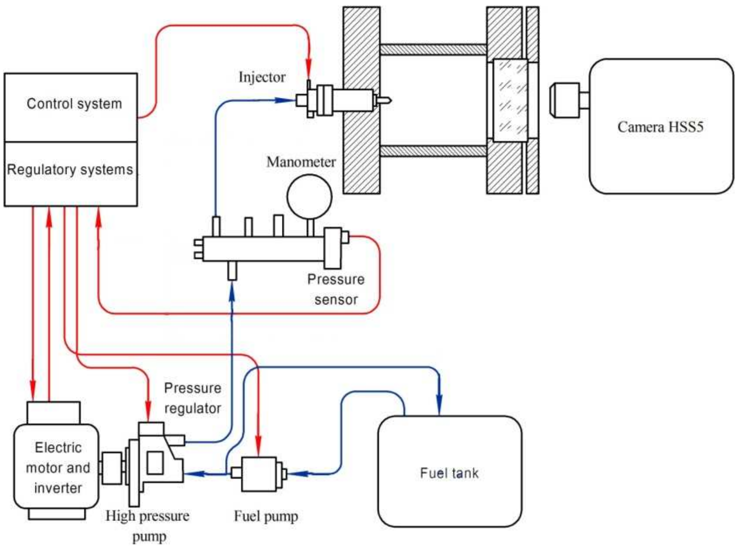


Figure 1. Test-stand for research on fuel spray evaluation

Scope of research. The research was conducted for two different values of injection pressure 20 and 25 MPa (Table 2). These values have been chosen as boundary ones typical for injection systems used today. The measurements were carried out in the research constant-volume chamber with the back pressure in the range 0.5-1.0 MPa, in all cases for the injection duration 600 μs. Recording of movies has been carried out in two manners. In the first one the camera was positioned perpendicularly to the injector axis – it allowed the analysis of the axial fuel spray penetration. In the second – the camera was positioned parallel to the injector axis and allowed radial spray penetration analysis (Fig. 2).

Table 2. Indexes of the research on gasoline injection into chamber with back pressure

No. –	Injection pressure P_{inj} [MPa]	Injection duration t_{inj} [μs]	Back-pressure of air P_{air} [MPa]	Test-code P_{inj}- P_{air}-t_{inj}
1.	20	600	0.5	200-05-06
2.			1.0	200-10-06
4.	25	600	0.5	250-05-06
5.			1.0	250-10-06

The analysis of the spray penetration, spray area velocities of its changes were processed in the computer with the use of DaVis program implemented by own programmes worked out on the basis of Command Language CL [4]. The fuel spray penetration was determined according to the algorithm (Fig. 3a):

- the initial position for fuel outflow from the injector was determined from X and Y coordinates;
- the fuel spray penetration values were determined for a single picture as a result of analysis of the entire width of spray of injected fuel and on the basis of its luminance;
- velocity of medium penetration of dose of injected fuel was determined;
- by taking into account time intervals between subsequent pictures, velocities of propagation of injected fuel spray front were determined.

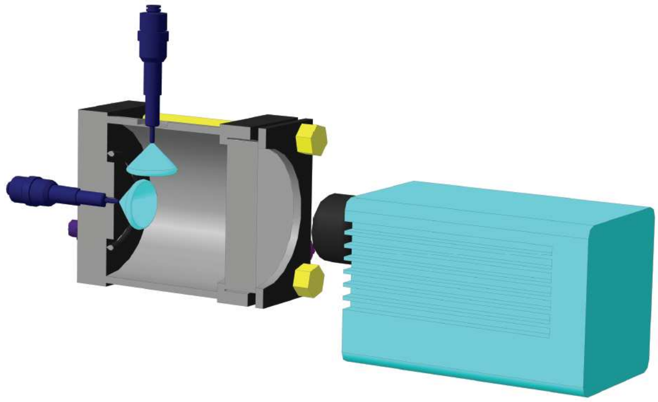


Figure 2. Location of the injector in the research chamber and the positioning of the camera

The radial penetration of the spray was determined according to the following algorithm (Fig. 3b):

- the initial position of the injector centre was determined by X and Y coordinates;
- the values of fuel spray penetration for a single picture were determined by way of analysis of the full angle of fuel outflow from the injector and on the basis of its luminance;
- the value of medium radial penetration of the injected fuel dose was determined;
- by taking into account time intervals between subsequent pictures, radial velocity of propagation of injected fuel spray cone front were determined.

a) b)

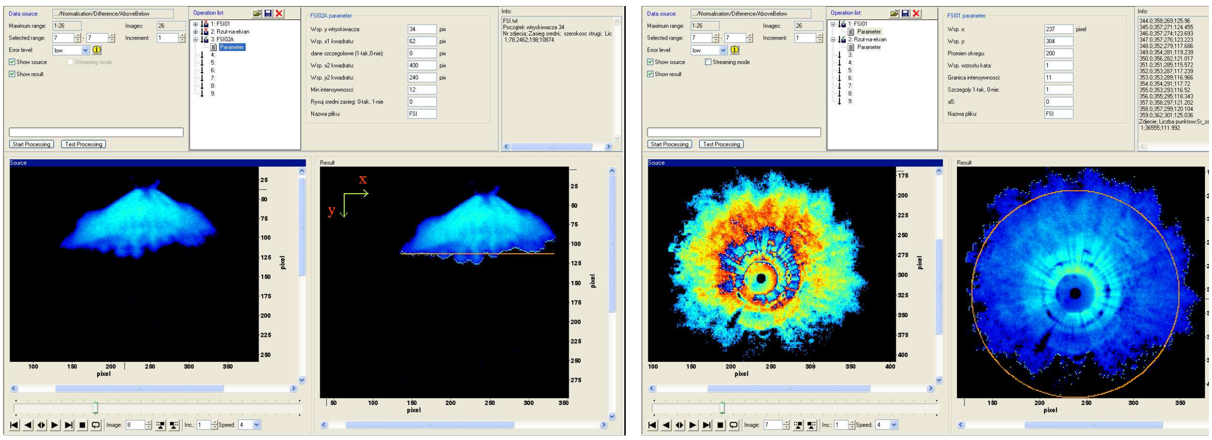


Figure 3. Evaluation of fuel spray penetration in the DaVis numerical program:
a) axial penetration; b) radial penetration

Influence of injection pressure and back-pressure on the fuel spray penetration

Axial spray penetration

Axial spray penetration was determined as the distance of the visible fuel spray front from the injector nozzle along the injector axis. The mean value of the distance was determined as arithmetic average from the sprays along cone generating lines on circumference of the spray cone. This value has been marked as horizontal line in Fig. 4 where the examples of the observations of the spray evaluation for the injection pressure 20 MPa, two values of air back-pressure and two phases of injection denoted by the time have been shown. The results obtained from such analysis are presented in Fig. 5.

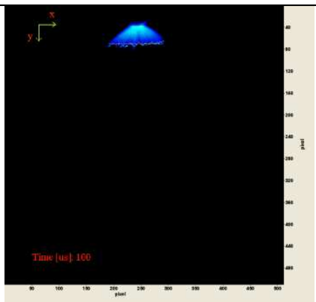
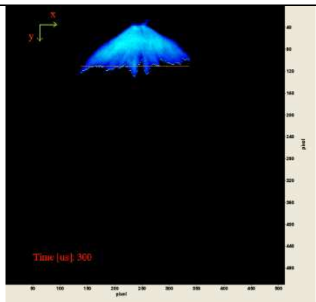
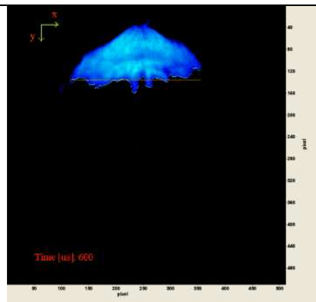
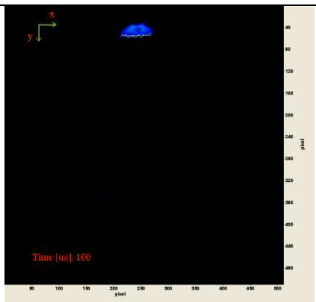
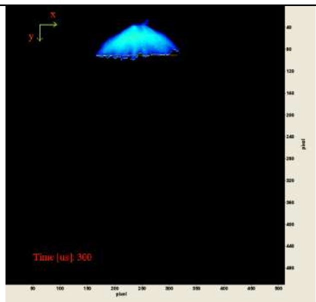
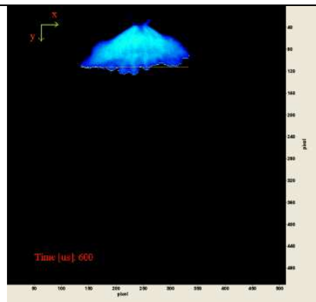
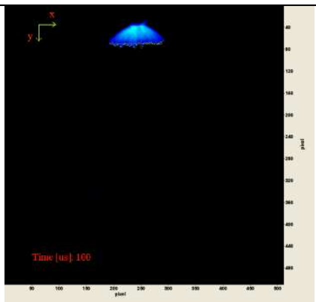
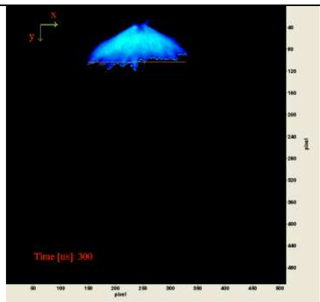
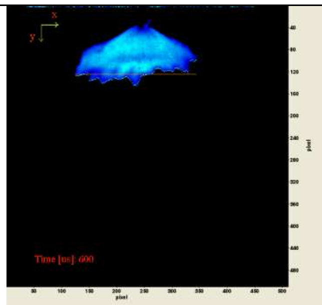
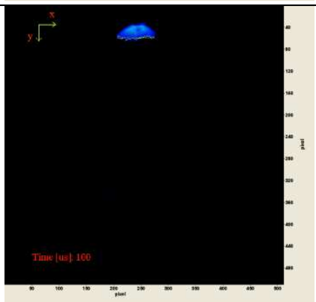
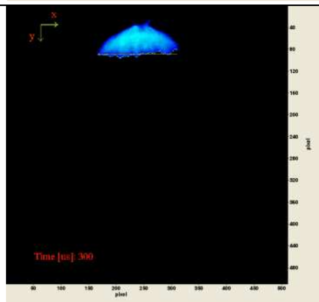
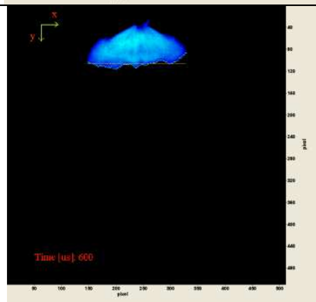
P_{air}	Gasoline injection pressure P_{inj} = 20 MPa		
	Time from SOI [μs]		
	100	300	600
0.5 MPa			
1.0 MPa			
	Gasoline injection pressure P_{inj} = 25 MPa		
	Time from SOI [μs]		
	100	300	600
0.5 MPa			
1.0 MPa			

Figure 4. Pictures of the axial fuel spray penetration for high-pressure gasoline injection into chamber with back-pressure (t_{inj} = 600 μs)

The quality of the fuel injection has been conventionally estimated taking into consideration the area occupied by the spray on its planar exposure in consecutive pictures from the recorded movies (Fig. 5b) and, additionally, the profile of fuel spray penetration. This profile specifies the dispersion of spray penetration along cone generating lines on circumference of the spray cone which were determined on the spray planar exposure as shown in Fig. 3b. The results are plotted against the distance from the injector axle (Fig. 5a) for the time t_1 = 300 μs after SOI (start of injection) (injection duration t = 600 μs). The dotted lines denote the average value of spray penetration obtained in the manner mentioned above. Fig. 6a shows examples of fuel spray penetration profiles (for fuel injection pressure of P_{inj} = 20 MPa) for two different air back-pressure values. A great diversity of spray profile of the injected fuel is visible. The growth of air back-pressure value is accompanied by a decrease in the changes in the spray profile (deviations are lesser than the medium value) for the growth of back-pressure from 0.5 to 1.0 MPa the width of the spray decreased by 25% (from 16.8 to 12.5 mm). Similar changes affected the area occupied by the fuel spray. It was determined as a projection onto the flat surface. Assuming the area occupied by the fuel spray as a reference point for the back-pressure equaling 0.5 MPa, it was confirmed that the area decreased by 25% and the back-pressure decreased to 1.0 MPa (Fig. 5b). The maximum changes of areas occupied by the fuel spray appear in the final stage of the injection (for t = 2.4 ms from the beginning of injection) and amount to 82% (P_{air} = 1.0 MPa).

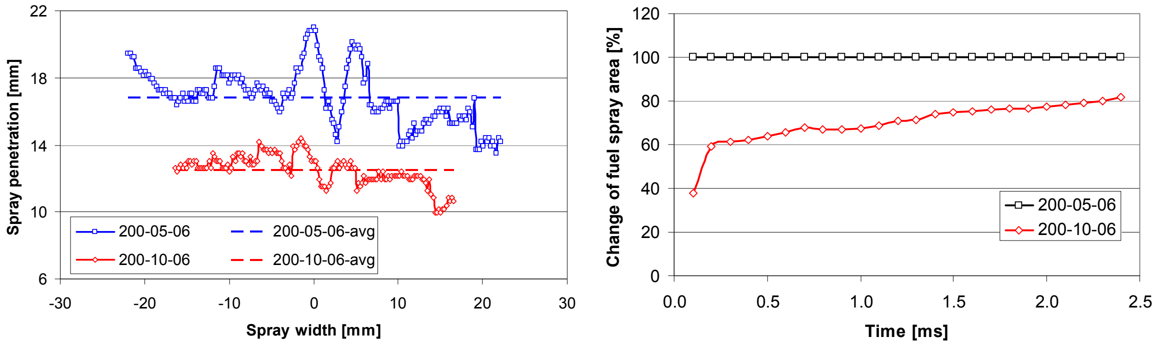


Figure 5. Fuel spray indexes: a) profile of fuel spray penetration; b) changes of the area occupied by fuel planar exposure of the spray [%] (P_{inj} = 20 MPa; back-pressure P_{air} = 0.5; 1.0 MPa; t_1 = 0.3 ms; t_{inj} = 0.6 ms)

Radial penetration of the fuel spray cone

Radial penetration of the spray was determined as a distance between the spray from the injector centre for parallel position of the camera and the injector (see example in Fig. 3b). The penetration was determined for tree times, namely t_1 = 100, t_2 = 300 and t_3 = 600 µs after SOI, for different values of the injection pressure and the back-pressure as results from the fuel spray pictures presented in Fig. 6 and Fig.7. The medium penetration was analysed as a result of an averaged penetration determined for each angular position of the radius along the entire circumference. The values of radial spray penetration and areas occupied by the fuel as determined with the use of recorded material as in Fig. 6-7, are shown as graphs in Fig. 8.

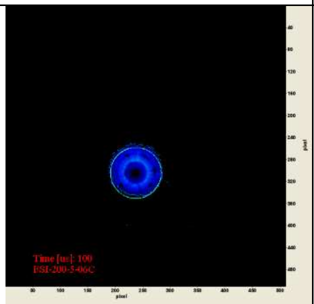
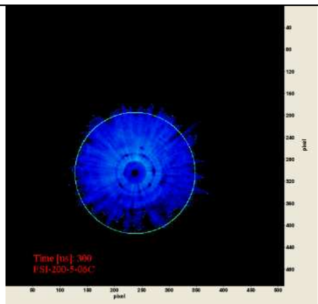
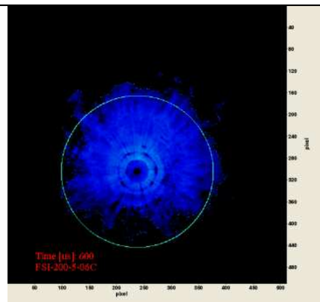
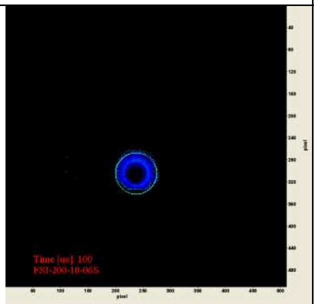
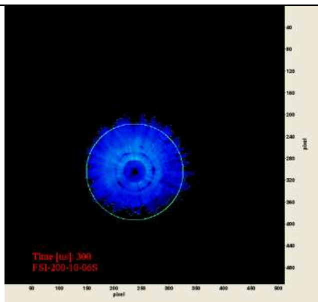
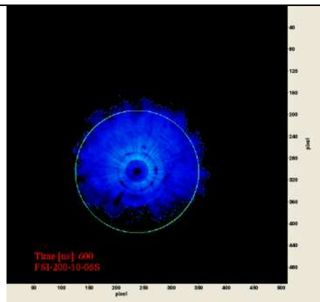
P_{air}	Gasoline injection pressure P_{inj} = 20 MPa		
	Time from SOI [µs]		
	100	300	600
0.5 MPa			
1.0 MPa			

Figure 6. Pictures of radial spray penetration by high-pressure gasoline injection into closed chamber with back-pressure (t_{inj} = 600 µs; P_{inj} = 20 MPa))

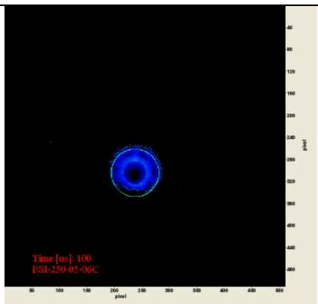
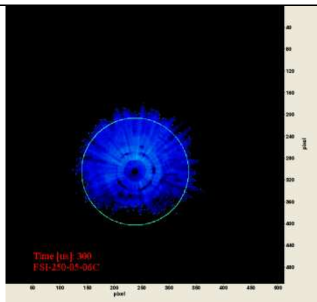
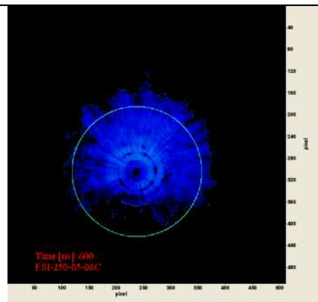
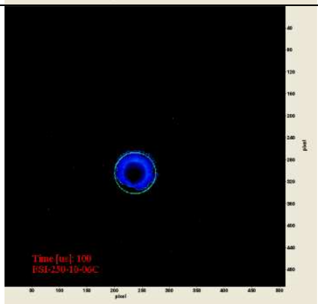
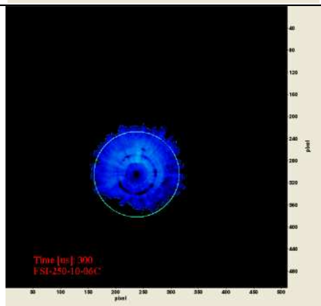
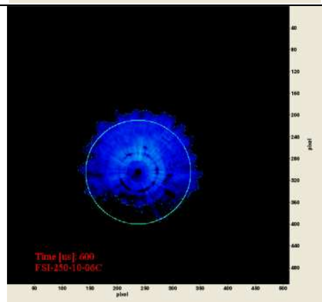
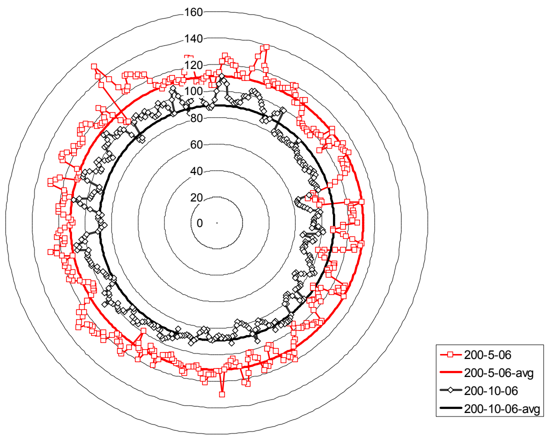
	Gasoline injection pressure P_{inj} = 25 MPa		
	Time from SOI [µs]		
	100	300	600
0.5 MPa			
1.0 MPa			

Figure 7. Pictures of radial spray penetration by high-pressure gasoline injection into closed chamber with back-pressure (t_{inj} = 600 µs; P_{inj} = 25 MPa))

The analysis of radial distribution of the spray penetration indicates that there are considerable deviations from the average value (Fig. 8a). The growth of the back-pressure causes a decrease of the spread around the average value. For the growth of back-pressure (0.5 to 1.0 MPa), the values of average square deviation decrease by 22% (for injection pressure of 20 MPa) and by 8% (for the change of back-pressure from 1.0 to 1.5 MPa). The increase of the injection pressure (P_{inj} = 25 MPa) causes a slight increase of the penetration spread (the growth of square deviation values by 3%). In this case, the growth of the back-pressure causes a decrease of the deviation by 13% (Fig. 8b).



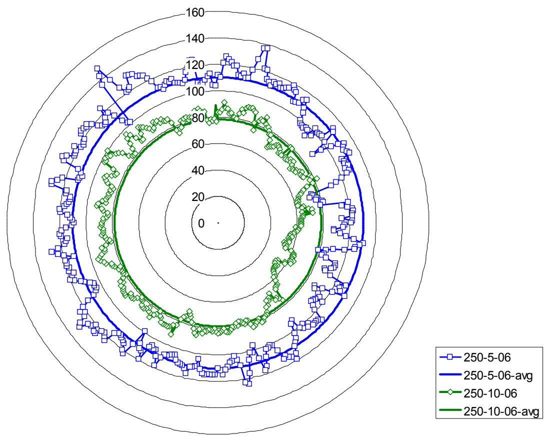


Figure 8. Influence of back-pressure values on radial spray penetration for injection pressures: a) P_{inj} = 20 MPa; b) P_{inj} = 25 MPa (t_1 = 300 µs; t_{inj} = 600 µs; back-pressure P_{air} = 0.5; 1.0 MPa)

The influence of fuel pressure on the quality of the end of the injection

The tests on the fuel injection with a high resolution disclosed the occurrence of the phenomenon of 'post injection'. Due to improper realization of the final part of the injection the final fragment of the fuel outflow from the injector was analyzed. The analysis was performed with the filming frequency of 20 kHz in the test points as shown in Table 3.

Table 3. The research plan of the fuel injection with a 'post injection' and the code forms used in further fuel investigations

Lp.	t_{inj} [μs]	P_{inj} [MPa]	Test code
1	500	10.0	500-100
2	500	12.5	500-125
3	500	15.0	500-150
4	500	17.5	500-175
6	500	20.0	500-200

The tests were performed for a constant fuel injection time at variable backpressures. From the characteristic of the piezoelectric injectors we know that the closing speed of the injector needle depends on the differences of pressures of the fuel occurring in different parts of the injector closed with stacks of piezoelectric plates. From the above we can assume that the pressure in the accumulator system will not cause a quick closure of the injector and, at the same time an abrupt end of the injection. The results of the observations confirm the assumption and show the actual conditions of the operation of the injectors – the existence of 'post injection' of duration up to 150-200 μs (Fig. 9). The results were obtained based on the analysis of the area of fuel outflow from the injector and determining of the brightness of the tested area.

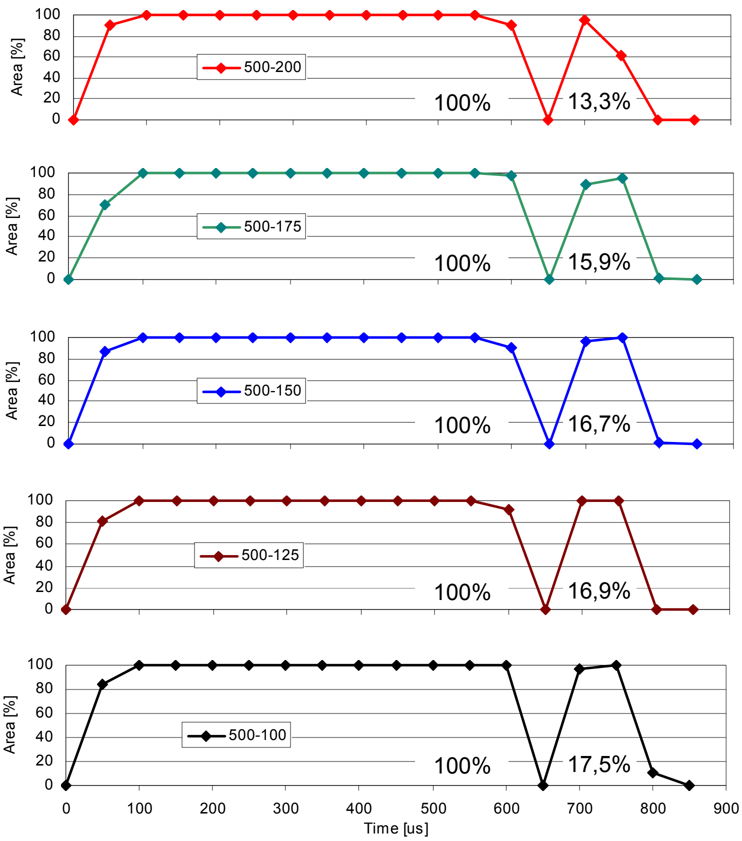


Figure 9. The analysis of the fragment of the area of the fuel outflow from the injector: determining of the duration of the 'post injection' based on the number of pixels in a given time interval (relative values; 100% denotes the whole fuel area under analysis)

The qualitative representation of the injector closing at different values of the fuel pressure in the accumulator (injection pressures) has been shown in Fig. 10. In order to analyze the fuel injection images the background was erased from each presented image.

In order to determine the intensity and qualitative assessment of the 'post-injected' fuel an analysis of collective fuel outflow has been carried out on the above images. The results show the number of pixels corresponding to the respective 'post injection' durations and the collective number of pixels corresponding to the amount of injected fuel (Fig. 11). Such an action is needed as the fuel 'post injection' onsets are not identical and are independent from the filming frequency (not synchronized with it).

From the analysis of the graph results a relation that as the injected fuel pressure grows (at a constant duration of the injection t = 500 μs) the amount of the 'post-injected' fuel reduces. This relation is in line with the principle of operation of piezoelectric injector as higher injection pressure results in a quicker closing of the injection needle.

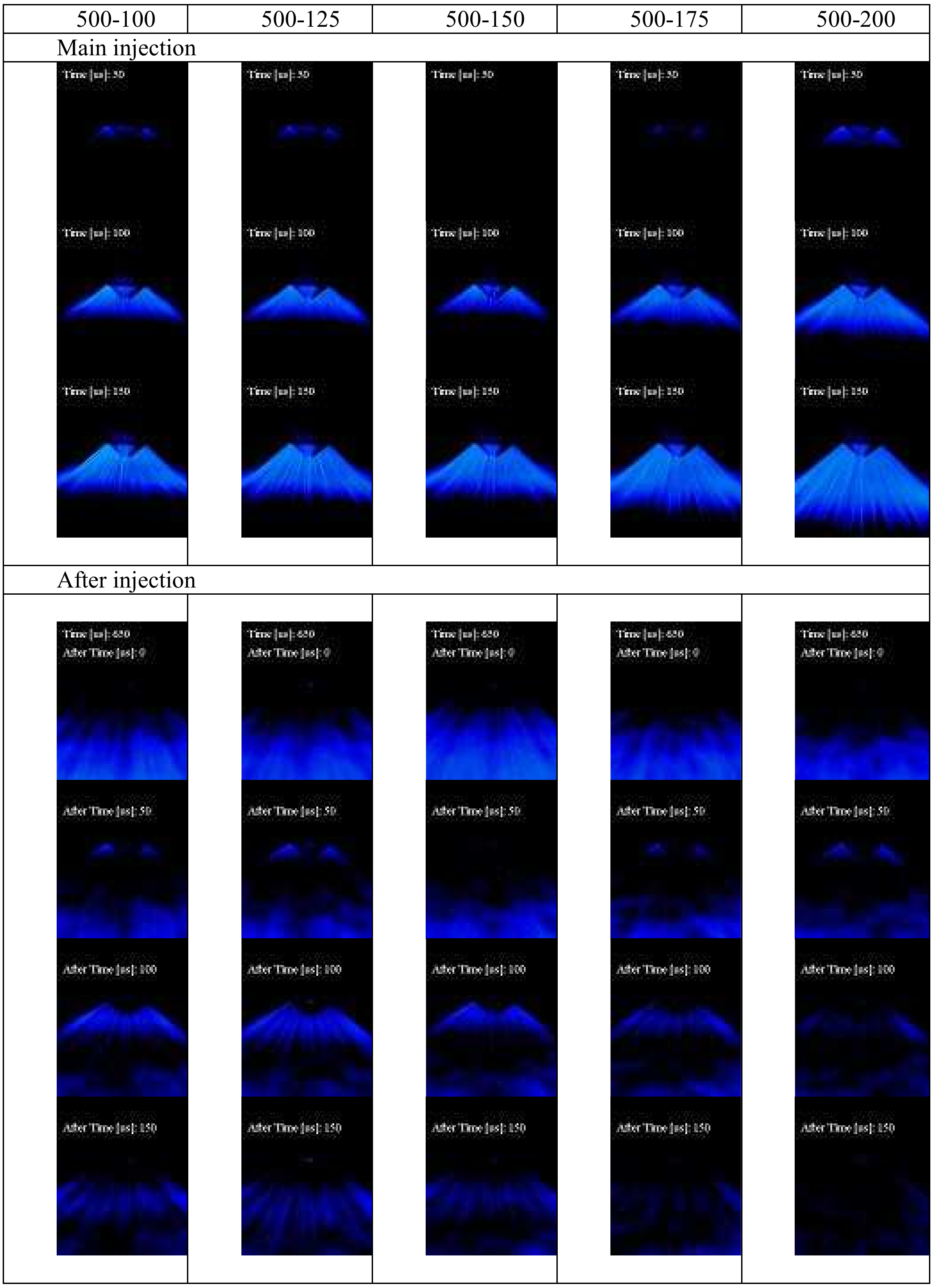


Figure 10. The influence of the gasoline injection pressure on the qualitative result of the final phase of the injection (the occurrence of the fuel 'post injection')

The size of the fuel 'post injection' depends on the fuel injection pressure. The maximum fuel 'post injection's have been observed for the fuel pressure P_{inj} = 12.5 MPa. The increase in the pressure results in a drop in the size of the ‘post injection’. The occurrence of maximum ‘post injections’ may be related to the occurrence of resonant frequencies for this type of fuel injectors. This forces the application of low (below 10 MPa) or high (above 17.5 MPa) fuel injection pressures in the injection system. The range between 10 and 17.5 MPa is the area of high ‘post injection’ occurrence.

The fuel spray penetration and uniformity were analyzed during the injection and ‘post injection’ at the same time parameters. Images were selected that correspond to constant times (100 μs) from the onset of the injection or ‘post injection’. A case was shown that causes a significant fuel ‘post injection’ (injection having the parameters t1 = 500 μs and the injection pressure 10 MPa – code 500-100). A qualitative analysis was performed of the fuel spray penetration: main injection and ‘post injection’ (Fig. 12).

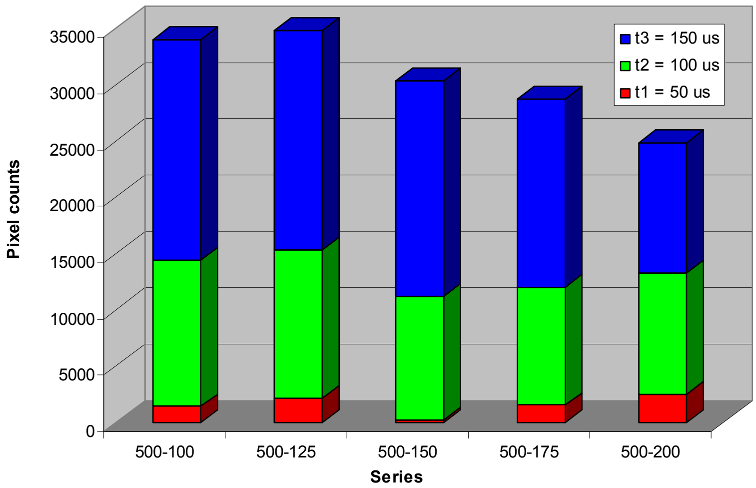


Figure 11. Changes in the number of pixels in subsequent phases of the ‘post injection’; the accumulated values in terms of quality correspond to the size of the dose of the injected fuel

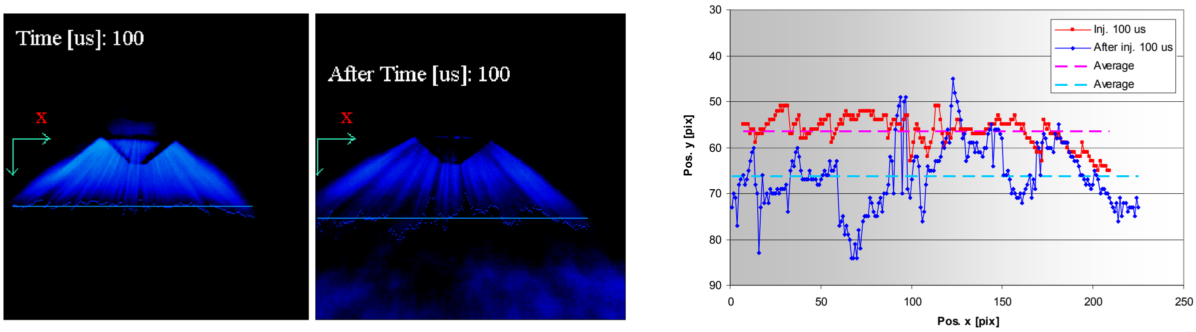


Figure 12. The analysis of the fuel spray penetration and uniformity 100 μs from the onset of the injection and 100 μs from the ‘post injection’

The average value of the fuel spray penetration grew by 17%; the width of the fuel spray also changed– it grew by 12%. The growth of the penetration during the ‘post injection’ is caused by the increase in the velocity of the fuel outflow – as a result of the change of the outflow diameter (when closing the injector). The fuel spray content and uniformity varies widely. During the main injection the average deviation amounts to 2.56. In the case of the ‘post injection’ the value is 5.65. From the above it results that in the case of ‘post injection’ the non-uniformity of the penetration grows twice as opposed to the main injection. The reduction of the number of pixels determining the fuel spray allows a conclusion that the pressure of this fuel dose is lower and the atomization is worse.

Conclusions

Based on the performed investigations we can conclude that:

1. As the backpressure grows the spread of the linear spray penetration reduces against the average value. These spreads – standard deviation – are reduced on average by 50% irrespective of the backpressure value. The reduction in the spray width is also visible as the backpressure grows. At the increase of the backpressure from 0.5 to 1.0 MPa the width of the spray reduced by 25%.

2. The growth of the backpressure results in a reduction of the fuel spray area. The maximum changes in the area refer to the onset of the fuel outflow from the nozzle. These changes amount to approximately 25% at the backpressure of 1.0 MPa).
3. A detailed analysis of the radial spray distribution indicates significant deviations in the spray penetration from the average value. The increase in the backpressure results in the reduction of the fuel spray spreads from the average value. The calculated average squared deviations indicate a 22% drop in the value as the backpressure grows by 50% (at the injection pressure of 20 MPa). The change in the fuel injection pressure by 25% results in an increase in the average squared deviation by 3%. The increase in the backpressure at this injection value results in the reduction of the deviation by 13%.
4. As the fuel injection pressure grows the amount of the 'post-injected' fuel reduces. At the increase of the fuel injection pressure by 50% a drop in the area covered by the additional fuel injection by 5% takes place. An increase by 100% results in the reduction of this area by 25%. From the above facts we conclude that the occurrence of the 'post injection' heavily depends on the fuel injection pressure.
5. The occurrence of the maximum 'post injection's may be related to the resonant frequencies for this type of injectors. This forces the use of low (below 10 MPa) or high (above 17.5 MPa) fuel injection pressures in the injection system. The range between 10 and 17.5 MPa is the area of high 'post injection' occurrence.
6. The analysis of the fuel spray, fuel injection and 'post injection' (the same time from the onset of a given fuel dose) indicates changes in the fuel spray penetration and width. The spray penetration increases by 17% and the fuel spray width by 12%. The non-uniformity of the spray penetration increases twice as determined by mean square deviation.

Nomenclature

P pressure [Pa]
t time [s]

Subscripts
air back-pressure of air
inj injection

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