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Comparative Analysis of Fuel Penetration and Atomization with the Use of Two Angularly Arranged Injectors in the Rapid Compression Machine and Constant Volume Chamber

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Abstract

The paper discusses the results of investigations into fuel atomization with the use of two high-pressure angularly arranged injectors fitted in a combustion chamber of Rapid Compression Machine and Constant Volume Chamber. The analysis relates mainly to the parameters of the fuel spray: spray penetration, observed fuel spray area in reference to both a single fuel spray and two angularly fuel sprays. The assessment of the uniformity of the fuel spray penetration for both sprays was carried out. The authors show a growth in the fuel spray volume and the reduction of the time of the fuel spray penetration during the angularly arranged injection at identical fuel doses (identical accumulative injection duration for a single fuel dose and two angularly fuel doses). Variable values of pressure and temperature realized in Rapid Compression Machine were identified. It was proved that that these values have a huge impact on evaporation conditions of fuel and, at the same time, on the area of sprayed fuel during injection and evaporation.

The tests were carried out for injection pressure 10, 15 and 20 MPa – values typical for modern high-pressure injection gasoline engines. The injection duration was 0.3 to 0.8 ms with different strategies. The optical investigations were carried out with the use of a high speed camera HSS 5 with the recoding speed of 10 and 20 kHz and the recording resolution of 256 x 176 pixels.

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Introduction

Gasoline direct injection is realized through a lateral or central location of the injector (a solution not too frequently applied due to technical difficulties). The lateral location of the injector allows sufficient time for the preparation of the charge for combustion because the injection is only possible before the piston reaches the Top Dead Center (TDC). This time is used for proper fuel evaporation and its preparation for combustion.

Currently, literature does not provide a full explanation of the physical aspects of the atomization and combustion of gasoline in direct injection systems. Insufficient quantitative and qualitative analyses of these processes encourage synthetic development of the methods of mixture preparation, its division and combustion in the aspect of the potential for control of the local and global engine processes.

The research on injection processes is mostly carried in stands with constant thermodynamic conditions. They are mostly ambient conditions [2] or CVC stands [7, 11, 12], in which research on geometric indicators of stream [3] or interaction between streams and walls, eg. combustion chamber [4, 13] is made. The research in variable conditions of pressure and temperature leads to complications of processes identification, but enables approximation research conditions to real engine conditions. The usage of transparent engine makes it possible to real processes identification [9, 10], but restricts recurrence of thermodynamic results.

The possibilities of research performed in close to real conditions but with larger possibilities of control mixture exchange processes enable Rapid Compression Machines [1]. The usage of them makes it possible to carry the research in dynamic conditions with higher research possibilities in the range of, for example, filming fuel stream.

The aim of the article was to specify the differences in fuel spray conditions during research on CVC and RCM. The authors led a research using two injectors, but the research was carried out on static conditions [5–7]. The research in RCM makes it possible to specify the implementation of this system in an engine.

Methodology

Research in fixed conditions was made in the Constant Volume Chamber (with variable parameters of pressure) for testing injection and atomization of liquid fuel, in which angular injection into the test chamber with two injectors was realized (in order to determine geometrical parameters of the fuel spray) – Fig. 1.

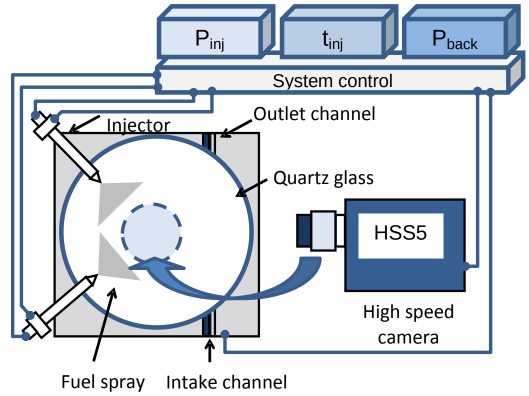

Figure 1. The Constant Volume Chamber with optical system for measuring fuel atomization.

The recorded images were analyzed using DaVis 7.2 by LaVision. The procedures of the Command Language CL constituted a basis for a development of own subprograms allowing determination of the following quantities:

– spray penetration
– surface area of the spray and the rate of its changes.

In the research on the injection the authors used a Constant Volume Chamber (Fig. 1) and Rapid Compression Machine (RCM) with an optical access inside the cylinder under the piston (Fig. 2). Such machines, due to their great research potential, are frequently used for the analysis of the process of injection and combustion as they reduce the costs and increase the speed of the tests compared with investigations utilizing transparent engines. The diameter of the quartz glass located in the piston crown amounts to 80 mm.

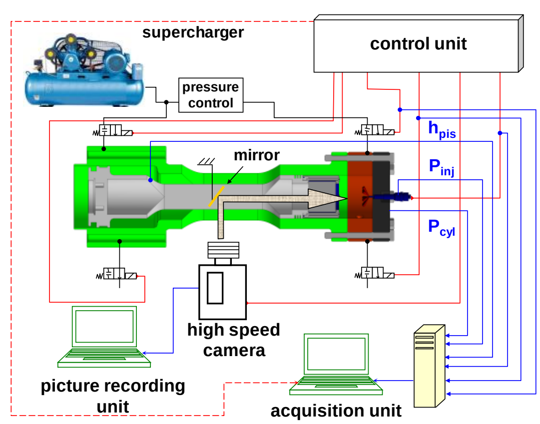

Figure 2. Schematics of the research stand.

For the control of the machine operation a system generating voltage signals was used and subsequently converted into such that allows the control of

Parameters	Constant Volume Chamber	Rapid Compression Machine
P_{inj} [MPa]	20	10
t_{inj} [ms]	0.3; 0.4; 0.6; 0.8	0.3
P_{air} [MPa]	1.5	~1.3

Table 1. Parameters of the tests in the Rapid Compression Machine and Constant Volume Chamber under investigation of fuel the injection.

the actuators (electromagnetic valves). This allows the setting of the system actuators: opening and closing of the intake of the control air (under the piston), opening and closing of the intake and exhaust valves above the piston, control of the fuel injector, electrical discharge of the spark plug and the onset of video recording.

In the investigations utilizing the RCM the following equipment was used:

a) additional devices:

– intake air pressure sensor – Keller PA21 SR,

– tensometric fuel pressure sensor – AVL SL31D-2000,

– piezoelectric combustion pressure sensor – AVL GM11D,

– piston travel sensor – contactless, potentiometric displacement sensor – Megatron LSR 150 ST R5k,

b) high-speed camera by LaVision, generating a sequence of images with the frequency of at least 10 kHz;

c) fast varying processes measurement system – AVL IndiModul (using charge amplifiers MicroIFEM). The measurements were subsequently the subject to processing in AVL Concerto V4.3.

The optical observations were conducted with the use of a high-speed camera that enabled filming of image sequences with the frequency of 10 kHz with the resolution of 512 x 512 pixels. Such conditions are sufficient for both the observation of the fuel injection and the analysis of its combustion.

Single fuel spray injection: the differences in radial and linear spray penetration

The filming of fuel stream in perpendicular directions causes the obtainment of linear or radial fuel range. In outward-opening injectors having 90 degrees gape of stream the indicators are related (Fig. 3). This dependences are related when no back-pressure is assumed during research.

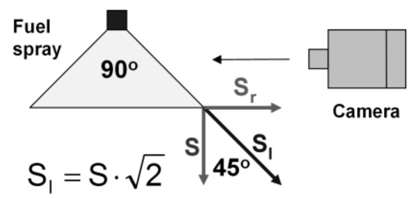

Figure 3. A method of determining linear and radial fuel spray penetration.

In the research led in Constant Volume Chamber with back-pressure similar to pressure in combustion chamber the dependences are not the same. Basing on the research on linear and radial range of fuel stream, the values different to 0.5 were obtained (when there is no back-pressure, the theoretical value is S_l/S_r = 0.5). When the injection pressure is high, the dependence is bigger than 0.5. After crossing 0.8 ms (all dose is injected) the linear range dominates on radial range. It impacts on increase of the length of penetration over crosswire penetration.

But in the situation when back-pressure is lesser (with constant injection pressure) the higher radial penetration is observed.

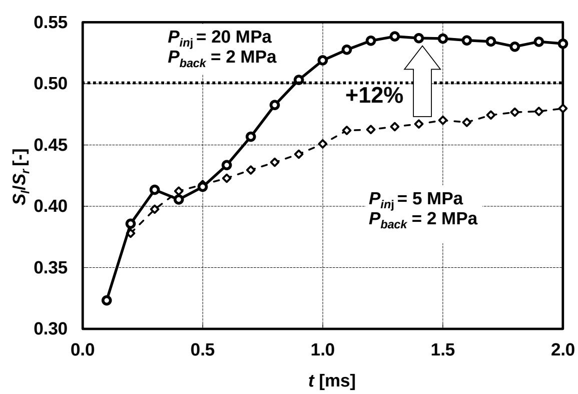

Figure 4. Linear and radial fuel spray penetration for one fuel injection (variation of fuel pressure); t_{inj} = 0.6 ms.

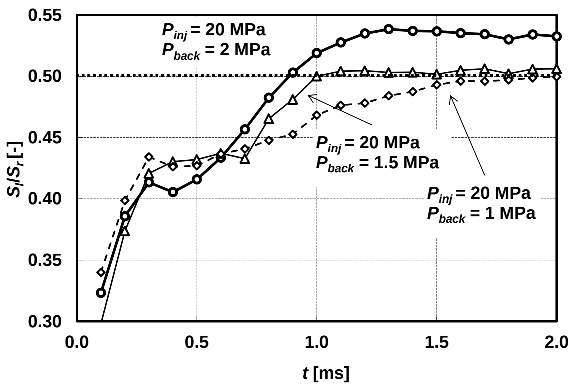

Figure 5. Linear and radial fuel spray penetration for one fuel injection (variation of back pressure); t_{inj} = 0.6 ms.

Fuel spray injection into Constant Volume Chamber

The use of two injectors in the fuel injection entails a need to properly locate them inside the combustion chamber. For this reason such a fuel atomization inside the chamber during the injection ensured that the fuel spray was not directed on the chamber walls. At the same time the fuel had to reach the spark plug in order to achieve proper ignitability of the formed mixture. These requirements were fulfilled by placing the outward-opening injectors at an angle of 45^o against the cylinder axis. The view of the fuel atomization by a single injector is presented in Fig. 6. The analysis of Fig. 6 indicates that the location of the injector at an angle allows a penetration of a single fuel spray that reaches the spark plug electrodes (in the area between the injectors). The influence of a single fuel dose on the geometrical parameters of the fuel spray was analyzed. Two injection times were applied t_1 = 0.6 ms and t_1 = 0.8 ms at a constant value of the air backpressure (P_{back} = 1.5 MPa). The penetrations and areas of the fuel spray were compared. From the applied settings it results that the increase in the injection time by 33% (from 0.6 to 0.8 ms) results in a mere 25% increase of the mass of the fuel dose. The fuel spray penetration increases by 4.4% (Fig. 6) and the fuel spray area increases by 13.7% (Fig. 7). This means that an increase in the fuel dose results in a significant increase in the area occupied by the fuel spray. It is noteworthy that the rate of increment of this area in both cases is similar. This means that the rate of fuel spray coverage slightly changes.

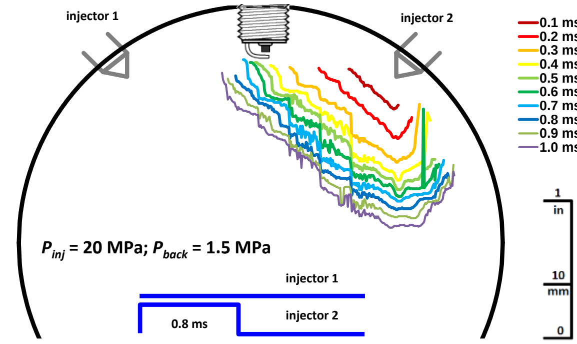

Figure 6. Fuel atomization sequence of a single fuel dose in the constant volume chamber (colors denote subsequent fuel spray penetrations (determined via DaVis)).

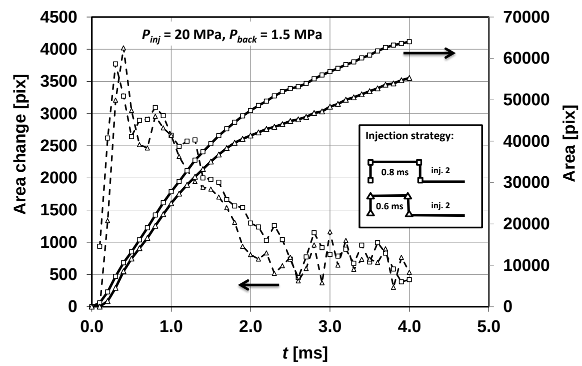

Figure 7. The influence of the fuel dose quantity on the fuel spray area and its change rate.

Two fuel doses were injected by two methods: simultaneously by two injectors and sequentially by two injectors. The view of the simultaneous injection with the fuel spray penetrations marked in the subsequent stages is shown in Fig. 8.

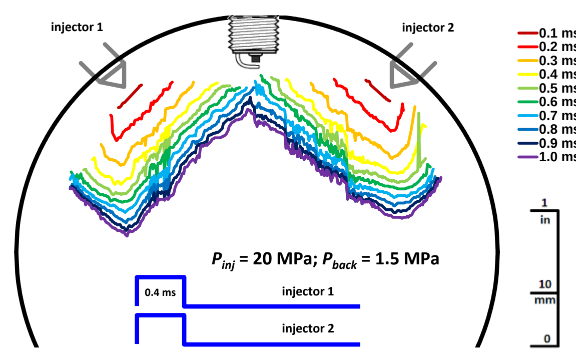

Figure 8. Fuel spray atomization in the constant volume chamber during a simultaneous injection of fuel via two injectors.

Figure 6 shows the combination of the two fuel doses which occurs in the location of the spark plug. In the research the problem of ignitability has not been considered but only the atomization of the fuel sprays. Yet, the location where the fuel sprays overlap clearly indicates the necessity of placing a spark plug there. Previously conducted research [6] indicates that the central location of the spark plug is most appropriate in terms of ignition at different quantities of the simultaneously injected fuel doses.

A dwell time between the fuel doses results in a greater area occupied by the two simultaneously injected fuel doses (Fig. 9). Yet, after time t = 3.0 ms the areas of the fuel spray get equal and no other deviations are observed. This means that the changes related to the fuel dose size, change in the order of the injections and their dwell times influence the fuel spray area only in terms of the times from the start of the injection until 2 ms after.

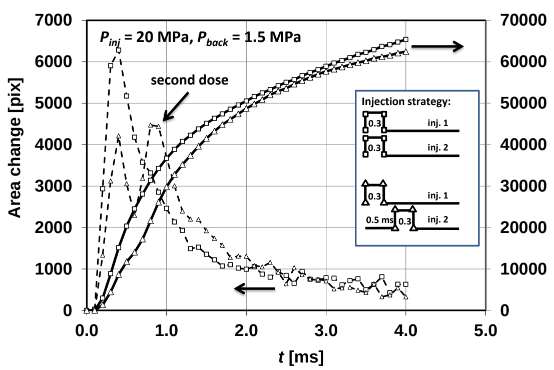

Figure 9. The influence of the fuel dose order on the fuel spray area and its change rate when injected by two injectors simultaneously.

An injection of three fuel doses leads to a possibility of obtaining of a better charge homogenization. Hence, a better fuel spray penetration into the combustion chamber becomes possible. As confirmed in the research the range of the mixture ignitability when three fuel doses are injected in a conventional way (a single injector) is greater. It also leads to a limitation of the misfiring trend when spray-guided direct injection is realized. In a conventional system, however, the possibilities of multiple injection are limited mainly when the engine is under high loads. The realization of the injection with two injectors allows reduction of the time for mixture formation and an injection of a greater mass of fuel in time.

Investigation on fuel spray injection into Rapid Compression Machine

Experimental research on fuel spray in Rapid Compression Machine was made by using the same CVC injection system. Due to the necessity of getting combustible of fuel mixture (combustion processes were not analyzed in this research) injection times and injection pressure are different than those used in CVC. This is why it is possible to compare the quality of indicators but it is not necessary.

The pressure analysis in Rapid Compression Machine in injection conditions is presented in Fig 10. The analysis has been made since the beginning of injection to spark ignition. In the results for single injection dose there is no big increase of pressure due to the short time of injection. Bigger amount of doses causes increase of injection time and simultaneously bigger increase of pressure. Therefore usage of two injectors in combustion chamber could evidently reduce fuel injection time while increasing stream penetration into combustion chamber. Through this strategy of sequential injection it is possible to get high homogenization of mixture while the injection time is shorter.

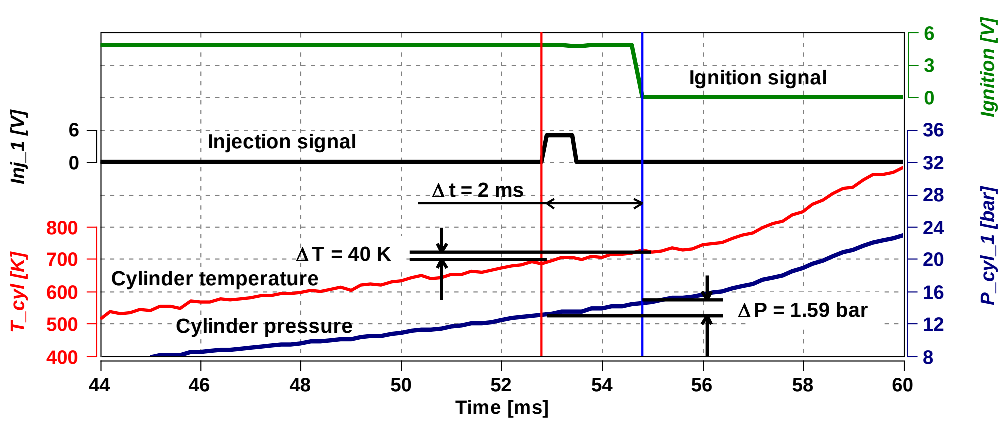

Figure 10. Pressure and temperature change during one-piece injection to RCM.

During the single dose injection the delay time between beginning of injection and ignition was 2 ms. In this time there was an increase of pressure ΔP = 1.59 bar (since 13.03 to 14.63 bar). This increase causes temperature increase equals ΔT = 40 K. It is important that the injection starts at T = 685 K and ends at T = 726 K. It means that area of observed fuel stream will be significantly smaller than during injection into Constant Volume Chamber (in which there is smaller value of temperature). It means also that reduction of stream area caused evaporation of fuel (with simultaneously light deterioration in combustion chamber).

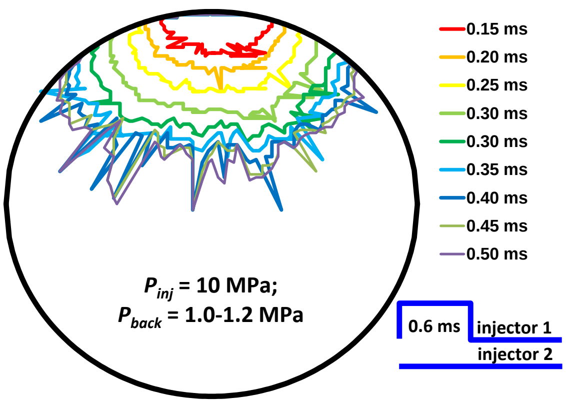

Figure 11. Fuel spray atomization in the RCM during a one fuel dose injection.

The analysis of fuel spray indicates existence of the maximum of stream in combustion chamber in RCM, but after time t = 0.7 ms follows sharp reduce of area. It is caused by an intensive evaporation of injected fuel into air with temperature T = 685 K. Next, the area of stream disappears causing inability to film and recognize the area. This is the reason for which on Fig. 11 the time of identification ends at time t = 0.5 ms.

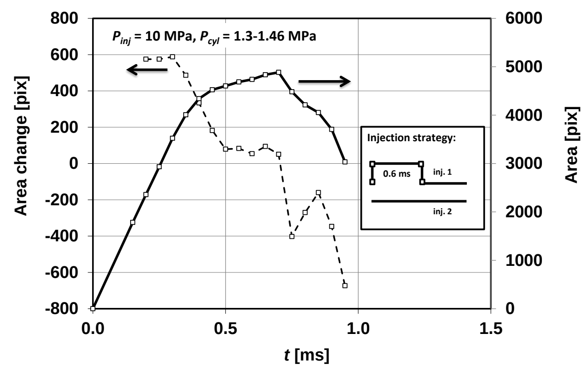

Figure 12. The change of area of fuel stream during single dose injection in Rapid Compression Machine.

In two-part sequential injection of fuel the dwell time between start of injection of first dose and ignition equals 2 ms too. In this time the pressure increases by 1.25 bar. At the same time the temperature increases by 25 K. It is important that injection begins at 650 K and ignition is on 675 K.

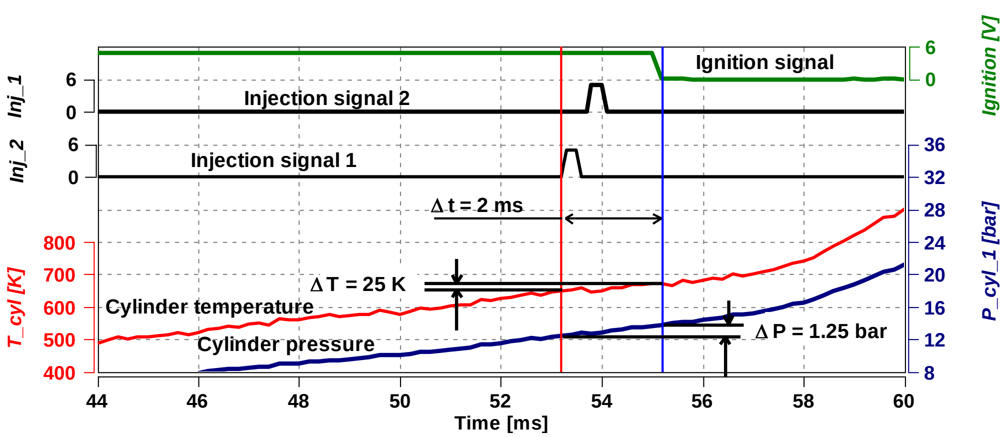

Figure 13. Pressure and temperature change during two-piece injection to Rapid Compression Machine.

It follows that the area of observed fuel stream will be definitely smaller than during the injection into CVC (where there is much smaller value of temperature). Slightly smaller values of pressure and temperature than during injection of single dose were also obtained. These changes are not significant and indicate only lack of the same conditions like in Rapid Compression Machine. But the level of obtained values of pressure and temperature is close enough to assume that the injection is in the same (or very close) thermodynamic conditions.

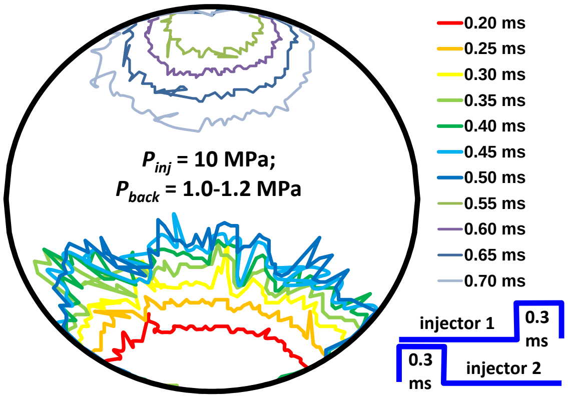

Figure 14. Fuel spray atomization in the RCM during a sequential fuel injection by two injectors.

The sequential injection of two doses allows to ascertain a high speed of evaporation out of both of them. It is especially evident because of much less injection times. In this situation the time of injection of both doses equals t = 0.3 ms. After the injection end, it is possible to specify the range of stream, however in the place where stream starts to flow after time t = 0.35 ms, the stream disappears what is caused by evaporating. After time t = 0.55 ms the analysis of injection of second stream is possible, which makes observation of increasing area of fuel stream on Fig. 15 possible.

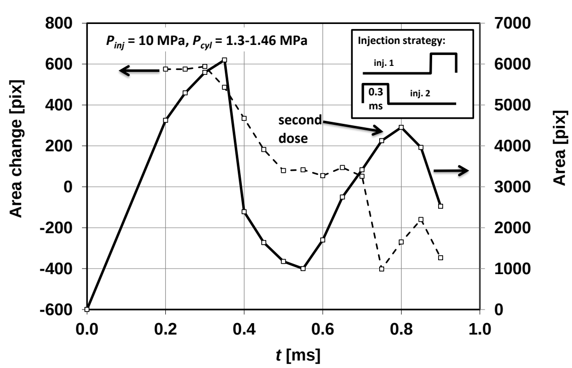

Figure 15. Change of fuel spray area during two part injection in Rapid Compression Machine.

Summary

Analysis of research in CVC and RCM enables to phrase conclusions:

a) Both research cases have different research conditions. Static thermodynamic conditions cause limited evaporation and also permit longer observation (injection range and area of stream is much longer than RCM)

b) Changing and bigger values of temperature in RCM cause that significant part of fuel evaporates and, at the same time, also limits possibilities to evaluate range and area of stream.

The range of future research in analyzed subject concerns:

a) The research in RCM enabling to analyze the injection and spray of fuel and simultaneously define ignition delay since ignition on spark to combustion.

b) Analysis of injection and spray of fuel with combustion process but without analysis of flame temperature. Usage of optical filters (two-color method) does not permit evaluation of fuel spray progress.

Nomenclature

P	pressure
t	time
T	temperature
CVC	constant volume chamber
RCM	rapid compression machine
S	spray penetration

Subscripts

inj	injection
air	air
back	backpressure
cyl	cylinder
l	linear spray penetration
r	radial spray penetration
1	first spray
2	second spray

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