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The control of the course of combustion in a DI SI engine through matching of the multiple injection strategy

The paper presents the results of the investigations of the dependence of the basic energy related indexes of the engine process on the strategy of direct multiple fuel injection. The tests were performed on a model engine – a Rapid Compression Machine. In the subsequent measuring cycles the injection strategy control (number of injected fuel doses, their size and dwell times) was modified. The courses of the combustion were observed through optical access and the possibility of recording of individual images of high spatial and time resolution. While processing the footage the velocity of flame formation and its development were determined as well as the main conditions of the flame propagation. Additionally, based on the observations and analysis of the spectral luminance distribution performed through a two-color method the temperature distribution was determined in the flame area. The investigations were performed for different injection strategies (multiple injection). It has been observed that the division of the injected fuel dose leads to the process of combustion, reduction of its duration and a reduction of the maximum flame temperatures. The fuel dose division is advantageous for the improvement of the efficiency of the oxidation process at lower temperatures approximating the phenomenon of low temperature combustion.).

Key words: *combustion in SI engine, optical research, multiple injection, low temperature combustion*

Sterowanie przebiegiem spalania w silniku ZI z wtryskiem bezpośrednim przez dobór strategii podziału dawki wtryskiwanego paliwa

W pracy przedstawiono wyniki badania zależności podstawowych wskaźników energetycznych procesu silnikowego od strategii sterowania bezpośrednim wtryskiem wieloczęściowym. Badania przeprowadzono na silniku modelowym, tzw. Maszynie Pojedynczego Cyklu. W kolejnych cyklach pomiarowych zmieniano strategię sterowania określoną przez liczbę wtryskiwanych dawek częściowych, ich wielkość oraz czasy między nimi. Przebiegi procesu spalania obserwowano wykorzystując dostęp optyczny do komory spalania i możliwość rejestracji poszczególnych obrazów z dużą rozdzielczością czasową i przestrzenną. W trakcie obróbki materiału filmowego określano prędkość powstawania i rozwoju płomienia oraz główne kierunki jego propagacji. Dodatkowo, na podstawie obserwacji i analizy spektralnego rozkładu luminancji przeprowadzonej z zastosowaniem metody dwubarwowej określano rozkład temperatury w obszarze płomienia. Badania zrealizowania dla różnych strategii wtrysku (wtrysk wielofazowy). Stwierdzono, że podział dawki wtryskiwanego paliwa prowadzi do procesu spalania, skrócenia jego czasu i zmniejszenia maksymalnych temperatur płomienia. Podział dawki sprzyja więc poprawie skuteczności procesu utleniania przy niższych temperaturach, zbliżając proces do tzw. spalania niskotemperaturowego.

Słowa kluczowe: *spalanie w silniku o ZI, badania optyczne, podział dawki paliwa, spalanie niskotemperaturowe*

1. Introduction

Spark ignition engines (SI) used in modern vehicles are not as uniform in terms of injection and combustion as diesel engines. In combustion engines both indirect injection (to the intake manifold, low-pressure) and direct injection systems (to the cylinder, middle- and high-pressure) are used. Designs that combine these two systems are very rare and did not become overly popular (engine by Lexus 2GR-FSE uses both direct and indirect fuel injection to the cylinder). Despite a variety of gasoline direct injection solutions fully satisfactory results in terms of engine operating parameters and exhaust emissions have not yet been obtained.

Direct injection of fuel into the cylinder should enable a homogenous combustion that is in fact realized in direct injection systems, yet charge losses occur before its delivery to the closed space of the cylinder. This system should also enable a formation of non-homogenous stratified charge that allows burning lean mixtures (currently the main trend in the global research and development). In this respect gasoline engines are becoming more similar to diesel engines.

The control of the course of combustion is one of the most widely discussed and most dominant research problems in recent years. The possibility of the ongoing control of the combustion process enables better operating indexes of the combustion system as well as the whole combustion engine. One of the methods of control of the combustion process is division of the fuel dose for a single working cycle and a proper adjustment of the injection times of the individual fuel doses.

This allows a free qualitative and quantitative control of the preparation of the combustible mixture and influences the character of its later combustion.

2. State of research on the effects of multiple injection in gasoline engines

The development of the first generation of direct injection systems in gasoline engines focused mainly on the wall guided fuel atomization. The second generation of the direct injection systems (spray-guided) has shown a potential that allowed a reduction in the fuel consumption through extending of the engine work area through charge stratification, with a simultaneous reduction of the exhaust emissions [15, 18]. Van Der Wege and others [18] pointed to the possibility of obtaining a stratified charge for high engine loads (effective pressure exceeding 0.5 MPa and engine speed above 4000 rpm) through the application of multiple injection. Also, the possibility was indicated of an improvement of the quality of the obtained homogenous mixture under high loads through an application of a wide-angle spray cone generated from an injector centrally located in the combustion chamber.

The first generation of engines fitted with direct injection systems (wall/charge-guided) enabled a reduction of the fuel consumption as compared to indirect injection systems (injection to the intake duct) thanks to the reduction of the pumping losses, advantageous conditions of operation on lean mixtures and lower heat losses at a lower charge temperature; The first generation also enabled the application of higher compression ratios thanks to the use of the cooling effect generated by the vaporization of the injected fuel [1, 2, 15]. In the case of spray-guided system of mixture formation the heat losses during combustion are lower, which leads to a further reduction of the fuel consumption. This solution is currently dominating in direct injection systems.

The advantage of this system of combustion is a central location of the injector near the spark plug, which allows a reduction of the delay in pressure growth after the ignition of fuel. Hence, we can more efficiently control the course of the combustion [8], the piston has a much larger area of heat transfer [15, 18] and as a result lower air swirl in the cylinder is necessary [17]. Contemporary research of combustion in s.c. transparent engines indicates that the fuel penetration at the end of the compression stroke is not sufficient to reach the piston area. This is confirmed by Raimann's investigations [14] carried out on outward-opening piezoelectric injectors. The fact that the fuel reaches the piston space causes increased emission of hydrocarbons and an increased opacity [3].

Frohlich and Borgmann [7] have shown that vehicles operated with piezoelectric outward-opening injectors have better fuel economy by 20% in relation to the vehicles fitted with conventional engines (IDI engines, medium unit power output 60 kW/dm^3). Wirth [22] in the investigations concerning the use of multihole injectors obtained 15.5% reduction in the fuel consumption as opposed to the PFI engine. He used the NEDC test as a basis for his comparison.

Apart from very few exceptions, in the literature there is no thermodynamic analysis of the engine work cycle using multiple injection and outward-opening injectors with an injector centrally located in the combustion chamber. Only the injection strategies are fragmentarily presented [5, 12, 19, 20] without their in-depth analysis. And also we will find elements of evaluation of the possibility of application of the strategy of multiple injection in the heating of the catalytic converter [4, 11].

The relevant literature does not provide a full description of the phenomena related to the physical aspects of fuel atomization in high-pressure gasoline injection systems nor the qualitative and quantitative analysis of its combustion. For this reason investigations have been initiated in order to search for qualitative and quantitative dependencies of the combustion process indexes from strategy of fuel dose division (considering the proportions of the division and the durations of individual doses).

3. Research equipment and methodology

Rapid Compression Machine

The investigations of the onset of the injection and combustion through optical methods are currently carried out in many research and development centers on real engines [9, 20] as well as in Rapid Compression Machines (RCM). The RCM utilized in Poznan University of Technology allows basic testing of a single work cycle of a combustion engine, particularly with respect to the fuel injection processes, charge motion, ignition and combustion. The machine is composed of a cylinder in which a piston is placed in such a way as to enable optical access to the combustion chamber from the direction of the piston crown (Fig. 1, 2); the option of optical access from the direction of the cylinder head is also convenient: this solution has been described in detail in [22] for the other case of research. The optical access through the piston crown allows using the whole area of the cylinder head to reflect the location of all the injectors and the spark plug.

Instead of a traditional crankshaft system a pneumatic system forcing the piston motion has been applied. For the control of the piston motion (compression stroke) the system uses air of adjustable pressure of up to 8 MPa fed to the area under the piston from an external air accumulator. The piston motion in the RCM fairly well reflects the operation of a real engine and corresponding thermodynamic indexes of the work cycle.

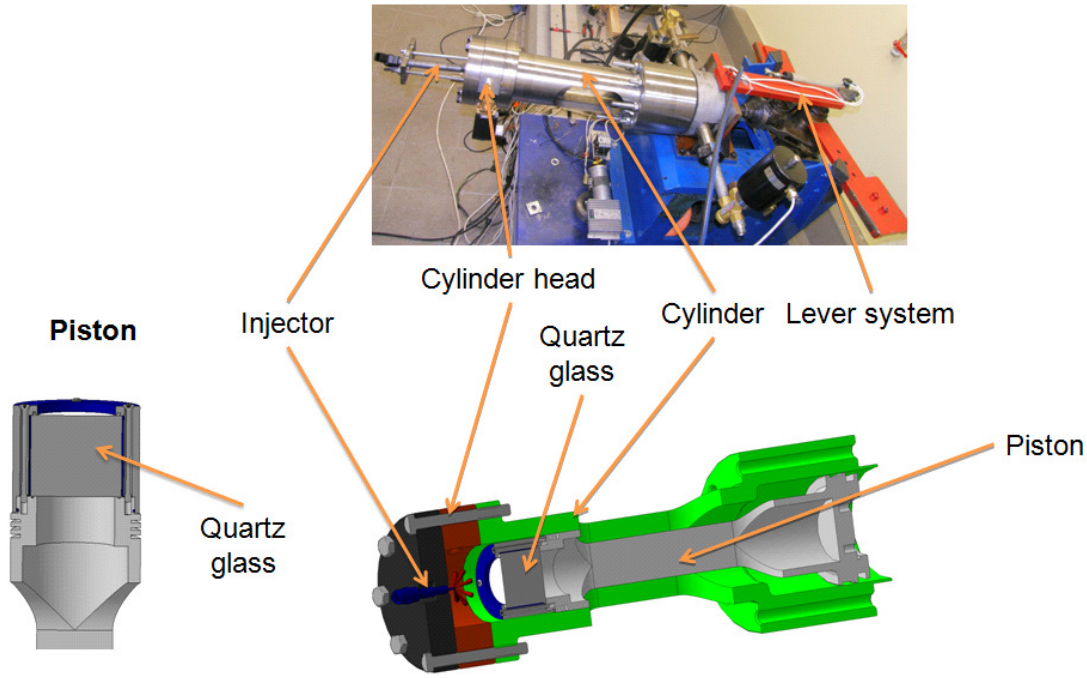


Fig. 1. The view and schematics of the Rapid Compression Machine with the optical access to the combustion chamber

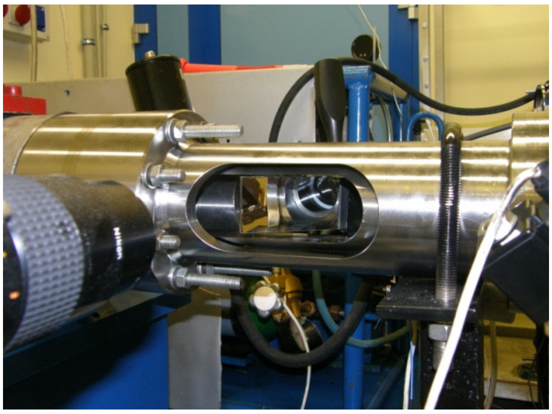
a)  b) 

Fig. 2. Rapid Compression Machine: a) optical access to the combustion chamber, b) cylinder head with the gasoline injection system and the fuel combustion pressure sensor

The operation of the RCM is controlled by a sequencer that generates individual signals to the actuators (electromagnetic valves). The system allows control in 16 channels with a resolution of ±1 nanosecond. The RCM can be fueled with positive ignition fuels (gasoline, ethanol, methanol and the mixtures thereof) and diesel oil (or alternative fuels like fatty acid methyl esters, eq. popular B100, or the mixtures thereof). Gasoline is fed from a standalone Common Rail fuel system of own design of operating injection pressure in the range of 5-30 MPa [23, 24]. A high-pressure pump (also used in BMW-engines) has been used in the system including outward-opening injectors [14]. The minimum injection time is 200 us, and the dwell time is 150 us (which corresponds to 0.006^o C.A. at engine speed of 4000 rpm).

The pressure measurements were performed with the use of a piezoelectric sensor AVL GM11D (sensitivity 2.52 pC/bar), the piston travel was measured with the use of contactless potentiometer displacement sensor LSR 150 ST R5k by Megatron. The indicator measurements were archived through AVL IndiModul (with the help of charge amplifies MicroIFEM), then processed in AVL Concerto V4.3.

Table 1. Technical data of the Rapid Compression Machine

Parametr	Value
Stroke	81 mm
Bore	80 mm
Cylinder displacement	407 cm^3
Combustion chamber volume	SI – 66.5 cm^3
Compression pressure	SI – 2.0 MPa
Type of comb. chamber	SI – hemisperical chamber + in piston crown
Piston breaking	pneumatic
Piston speed	30 m/s
Optical access	Quarz window ϕ48 x 50 mm in piston crown
Injection pressure	SI – 5-30 MPa
Combustion type	SI – homogenous and stratified mixtures

For the recording of the flame occurring in the combustion chamber a High Speed Star 5 camera (Fig. 3) by LaVision was used. The camera is fitted with a CMOS monochromatic image converter which allows recording of images with the resolution of 1024 x 1024 pixels (pixel size 17 x 17 um) with the recording speed of 2500 and 5000 frames/s (fps) and even more with reduced resolution. The spectral range of the recording is 380-800 nm. The analysis of the obtained images was done with the use of DaVis software by LaVision [6].

Fig. 3. The camera and the dual optics system

4. Flame temperature evaluation method

The flame images were recorded with a high-speed camera with the use of a technique of simultaneous recording of two images (using the appropriate part of the matrix of the CMOS converter) after passing through optical narrow-band pass filters. The flame images were processed in DaVis software. The temperature of the hot flame (in the visible range) was obtained with the use of software of Command Language CL implemented in the DaVis. After determining of the temperature of the hot flame in individual images and its distribution, the areas occupied by the flame of given temperature were indicated for the assumed accuracy (temperature range).

The temperature calculations were done based on the two-color method [10, 15], in which the radiation of bodies is described with the Planck's law:

$$M(\Lambda,T)=\varepsilon_\Lambda \frac{C_1}{\Lambda^5}\left(e^{\frac{C_2}{\Lambda T}}-1\right)^{-1} \qquad (1)$$

where: M (Λ,T) – spectral radiation intensity [W/m^3], C_1 – radiation constant (3.742 · 10^{-16} [$W\cdot m^2$]), 1. Planck constant, C_2 – radiation constant (1.4388 · 10^{-2} [m·K]), 2. Planck constant, T – temperature [K], ε – flame emissivity [–], Λ – wavelength [nm].

In the visible spectrum and in the near infrared (Λ = 380–800 nm), in the temperature range of up to 3000 K, the following condition is fulfilled: $C_2/(\Lambda\cdot T)>>1$. The Planck's law can then be substituted with Wien's law that has a form:

$$M(\Lambda,T)=\varepsilon_\Lambda \frac{C_1}{\Lambda^5}e^{-\frac{C_2}{\Lambda T}} \qquad (2)$$

The two-color method of radiator temperature determination consists in measuring of the radiation at two different wavelengths of the light waves and comparing the measured luminance. Its application is possible for known values of the flame at two wavelengths of radiation Λ_1 and Λ_2 or if this value is independent of the wavelength (the flame is treated as grey body).

The ratio of the spectral radiation intensity (M(Λ,T)) at two different wavelengths can be substituted with the ratio of the results of the luminance measurements (because M ~ L) in the range of two wavelengths respectively Λ_1 and Λ_2:

$$\frac{L(\Lambda_1,T)}{L(\Lambda_2,T)}=\frac{\varepsilon_{\Lambda 1}}{\varepsilon_{\Lambda 2}}\left(\frac{\Lambda_2}{\Lambda_1}\right)^5 \exp\left[\frac{C_2}{T}\cdot\left(\frac{1}{\Lambda_2}-\frac{1}{\Lambda_1}\right)\right] \qquad (3)$$

Solving the equation for the temperature we obtain:

$$T=C_2\cdot\left(\frac{1}{\Lambda_2}-\frac{1}{\Lambda_1}\right)\Bigg/\left[\ln\frac{L(\Lambda_1,T)}{L(\Lambda_2,T)}+\ln\frac{\varepsilon_{\Lambda 2}}{\varepsilon_{\Lambda 1}}+\ln\left(\frac{\Lambda_1}{\Lambda_2}\right)^5\right] \qquad (4)$$

For gas flames we assume that $\varepsilon_{\Lambda 1}/\varepsilon_{\Lambda 2}=\Lambda_1/\Lambda_2$. Then, the local temperature of the flame is calculated from the relation:

$$T = C_2 \cdot \left(\frac{1}{\Lambda_2} - \frac{1}{\Lambda_1} \right) \Bigg/ \left[\ln \frac{L(\Lambda_1, T)}{L(\Lambda_2, T)} + \ln \left(\frac{\Lambda_1}{\Lambda_2} \right)^6 \right] \quad (5)$$

During the tests the combustion process was recorded at the same time through two color filters and the luminance L of every pixel in the image was determined. Then, utilizing the calculation procedure, the temperature of a given area represented by the pixel from the proportion of luminance at different wave-length (eq. 5) was obtained. For a better interpretation of the temperature the iso-lines were performed in each range and as a final result the distribution of the temperature in the cylinder was obtained. The analysis of all the points of the image indicates the distribution of the temperature in the combustion chamber throughout the whole process, Fig. 4.

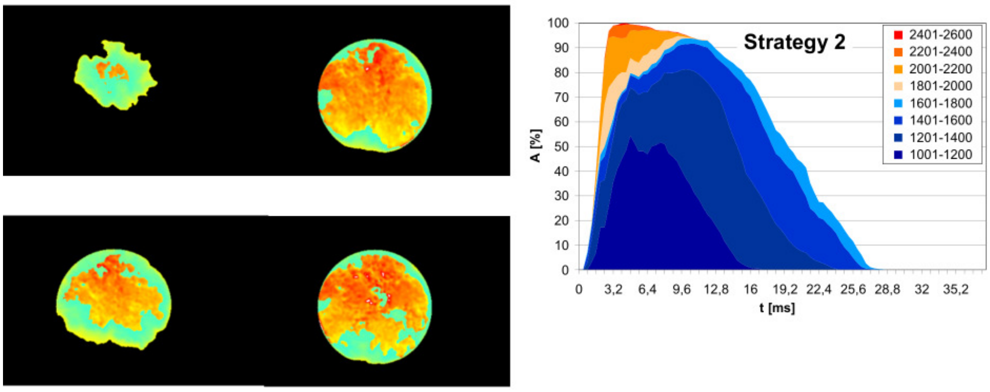


Fig. 4. Flame temperature distribution in the combustion chamber: a) temperature distribution in the planar exposition of the chamber, b) the history of the flame temperature distribution during combustion

5. Influence of the multiple injection on the combustion course

Research plan

The investigations of the combustion with the fuel dose division were carried out according to a plan presented in table 2. Research points without fuel dose division and with a division into two and three doses were used. The collective fuel amount and the air excess coefficient λ = 1.2 were preserved. The tests were carried out at the injection pressure of 10 MPa; at higher injection pressures the injection time is reduced due to a higher velocity of the fuel outflow from the injector (the flow characteristics of the injector was performed earlier). The fuel ignition occurred at the moment when the injection of the main fuel dose was initiated (or the undivided fuel injection).

Injection strategy

The tests on the selection of the injection strategy were carried out for the air excess coefficient in the cylinder of 1.2 (lean mixture). The fuel injection strategy was selected as follows: combustion without fuel dose division (strategy 1) at fuel injection pressure of 10 MPa; combustion with the fuel dose division into two parts (strategies 2-4) at the pressures of 10 MPa and the fuel dose division into three parts for the fuel pressure of 10 MPa (strategies 5-7). In the tests a fuel dose of 60 mg was used (for all fuel injection strategies). The ignition occurred at a given operating point of the RCM, which allowed a comparative analysis of the variability of the thermodynamic indexes.

Table 2. Strategies of the fuel dose division

Strategy	P_{inj} [MPa]	q_1 [ms]	t_1 [ms]	q_2 [ms]	t_2 [ms]	Ignition q_3 [ms]	t_3 [ms]	q_4 [ms]
1.	10					1.3		
2.	10			0.6	3	0.9		
3.	10			0.6	9	0.9		
4.	10					0.9	3	0.6
5.	10	0.3	3	0.4	3	0.8		
6.	10	0.3	1	0.4	3	0.8		
7.	10			0.3	3	0.8	1	0.3

Optical analysis of the combustion process

In order to explain the reasons for the changes of the determined thermodynamic comparative indexes depending on the applied injection strategy the authors also performed a recording of the combustion process in the cylinder. A digital analysis of the individual frames enabled determining of the additional physical indexes describing the formation and development of the flame in the combustion area. These were: instantaneous area occupied by the flame A [%] referred to the total area of the combustion chamber, the rate of the changes of that area dA/dt [m^2/s], linear velocity of the flame front displacement V [m/s] and the angle between the assumed horizontal line and the direction of the highest speed of flame displacement dF, Fig. 5. It has been assumed that the indexes determined based on the flat projection of the spatial image represent spatial course of the flame propagation.

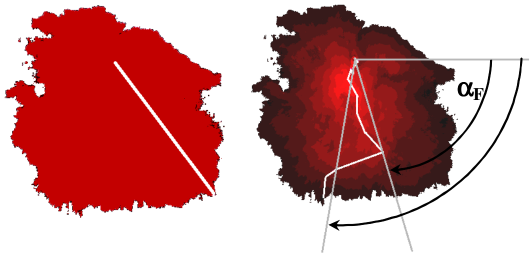


Fig. 5. Schematics of the determining of the angle of displacement of the flame front

Frame analysis of the recorded images enabled determining of the instantaneous parameters of the flame and the dynamics of their change with a resolution resulting from the recording speed and the image resolution. The research procedure was repeated for the above-mentioned strategies of fuel injection.

Example images of the flame for the combustion process with fuel dose division into two and three parts have been shown in Table 3. The area of the combustion chamber was not illuminated with external light so the injected fuel sprays before the ignition are not visible in the images. The differences are seen, however, in the spatial flame distribution that result from a different mixture preparation and its different composition.

As it results from the image analysis as shown in Fig. 6 the area occupied by the flame to a large extent depends on the realized injection strategy. If the fuel dose is not divided the time needed for the flame to fully penetrate the combustion chamber extends as shown in Fig. 6.

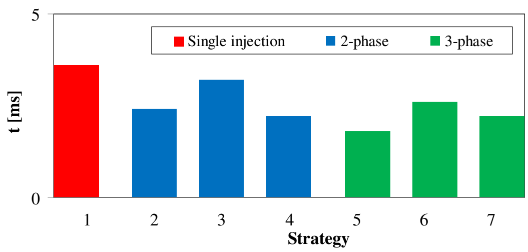


Fig. 6. Comparison of the full penetration time by the flame for different fuel injection control strategies

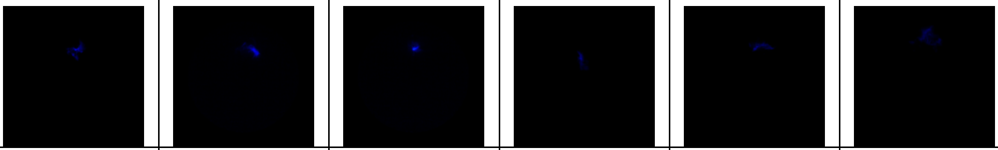
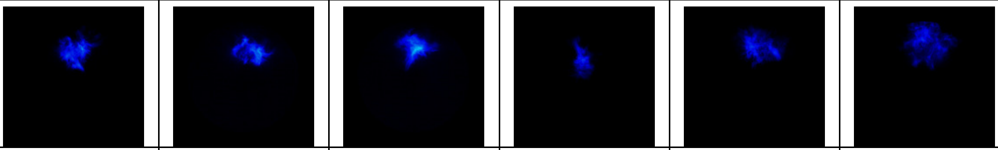
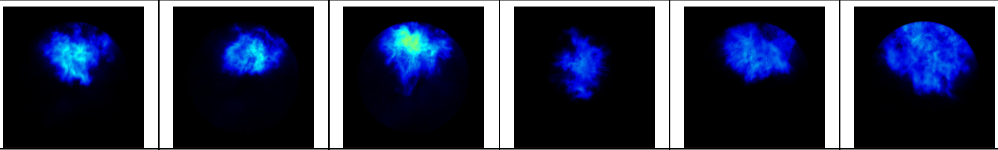
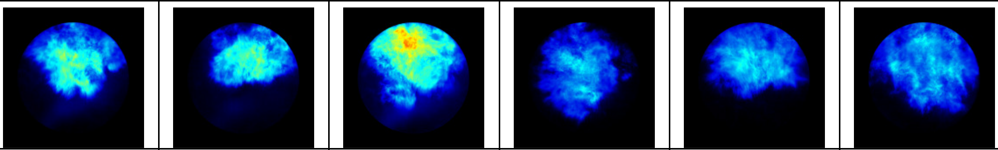
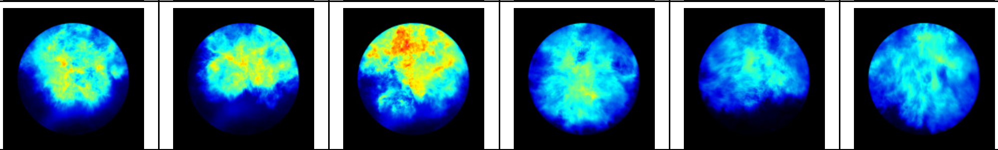
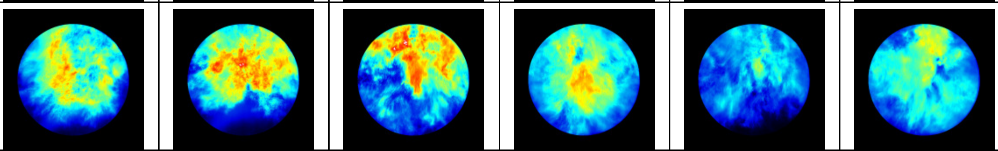
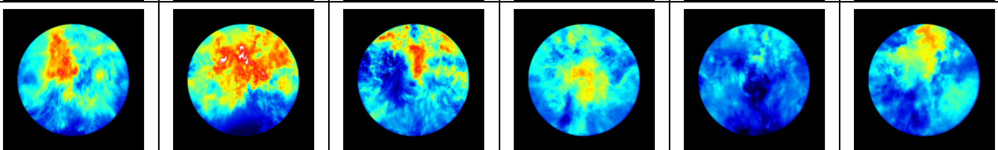
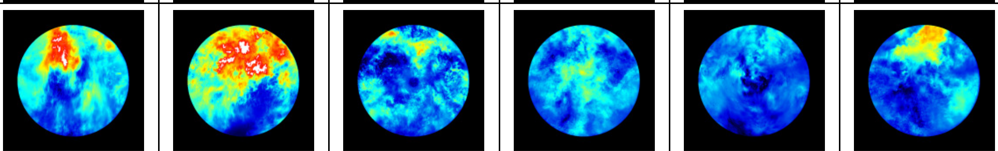
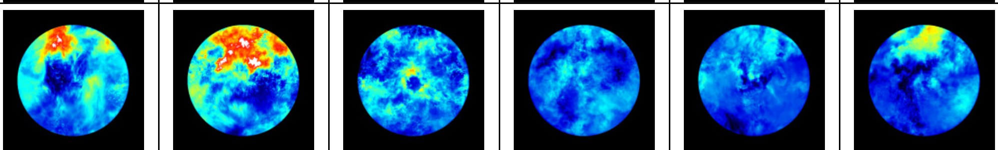
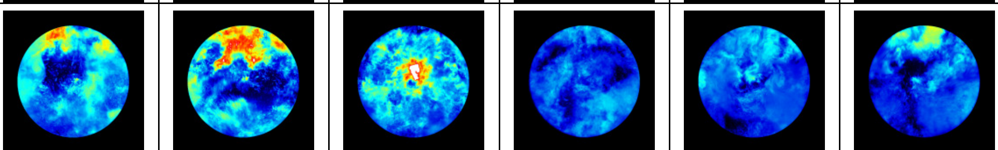
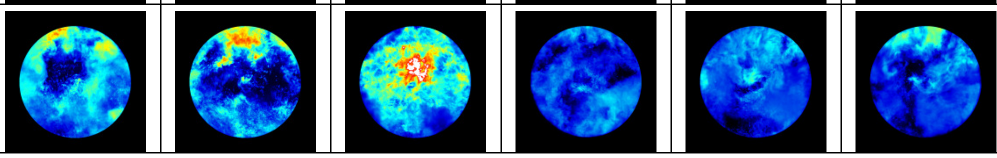
Based on the image analysis it has been observed that there are much lower combustion rates in the initial phase (until approximately 2 ms of the process duration) than for the strategy with the fuel dose division. The fuel dose division into three parts at high-pressure injection (strategies 5, 6, 7) results in the shortest time needed for the flame to penetrate the whole combustion chamber and at the same time it is characterized with the greatest dynamics of propagation, which denotes the growth of the combustion rate. Lower average temperatures of the cycle are characteristic here, which adds to the reduction of the exhaust emissions (nitric oxides in particular). The changes in the mixture composition and a reduction in the injection pressure results in the extension of the time after which the flame penetrates the whole combustion area.

For the subsequent images recorded the area covered by the flame was calculated and the time after which the flame penetrates the whole combustion chamber was determined. The shortest time was observed for the injection strategy 5 which was 1.6 ms from the start of the combustion, Fig. 7, where the start of combustion was determined as time of spark occurrence on the electrodes of the spark plug. The longest time (approx. 3.6 ms) was recorded for strategy 1 – without fuel dose division at the pressure of 10 MPa. It was also observed that in the case of strategy 5 the dynamics of the flame propagation in the early combustion was the greatest (after approx. 1.6 ms, Fig. 7b). Strategy 1 without fuel dose division and strategies 2, 3 with the fuel dose division into two parts lead to slower flame propagation in the beginning of the process and its acceleration in the further part of the process (approx. 2-2.5 ms).

The analysis of the velocity of the flame propagation indicates that the higher the velocity the shorter the process of combustion. It depends on the fuel dose division or the lack of its division but it does not depend (in the initial phase) on the number of injected fuel doses before the ignition (Fig. 7c). The greatest velocities of the flame front are obtained for the fuel dose division into 3 parts. This indicates the growth of the rate of combustion and a better flame propagation, thus creation of better conditions for oxidation and combustion in the case of multiple injection. The rate depends on the fuel concentration in the vicinity of the spark plug. The distribution of fuel in the combustion chamber depends on the fuel dose division (or the lack of its division). The tests conducted without the charge swirl in the cylinder indicate no influence of the fuel injection strategy on the angle of (direction) the maximum flame velocity (Fig. 7d). This angle, apart from few examples (sometimes resulting from the impossibility of its precise determination based on the image), does not change significantly in any of the strategies.

The analysis of the images allowed a relatively precise determination of the end of combustion. It was assumed that the end of combustion would be deemed as the end of the recorded flame illumination area; due to an impossibility of recording

Table 3. Combustion images obtained for different strategies of multiple injection, in the time of 4.4 ms of the process duration

Time after SOC [ms]	Strategy					
	2	3	4	5	6	7
0.4						
0.8						
1.2						
1.6						
2.0						
2.4						
2.8						
3.2						
3.6						
4.0						
4.4						

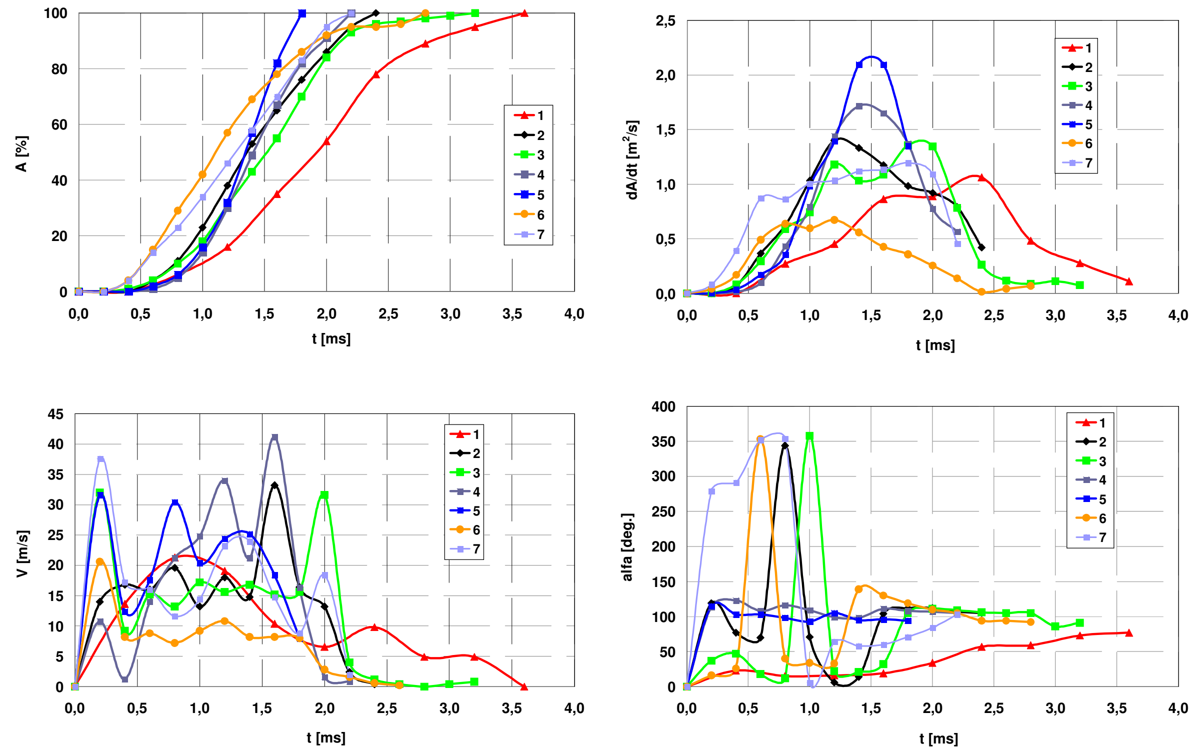


Fig. 7. Analysis of the parameters of the flame front based on the images of the combustion chamber

infrared radiation is not included. The growth of the number of fuel doses reduces the time of combustion. The fuel dose division at high pressure injection into three parts – strategies 5, 6, 7 results in the shortest time of the combustion process (Fig. 8) and at the same time is characterized by the greatest process dynamics, which denotes the growth in the combustion rate (Fig. 7). Lower temperatures of the cycle are reached here which adds to the reduction of the exhaust emissions (nitric oxides in particular). The changes in the realization of the injection phases and a reduction in the number of fuel doses result in the extension of the time after which the flame penetrates the whole combustion area (strategies 2, 3).

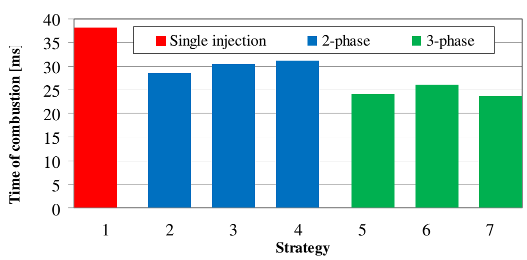


Fig. 8. Comparison of the combustion time for different injection control strategies

The application of an additional fuel injection (strategy 4) after the start of the combustion results in higher temperatures of the cycle than the strategies without post injection (as presented in Fig. 9). At the same time, the additional fuel injection (strategy 7) after the start of the combustion results in lower temperatures of the cycle than it is in the case of strategy 4. The conclusions were drawn based on the optical observation. The post injection results in a growth of the areas of more intense illumination. This is related to the radiation of soot, which may result in a growing emission of particulate matter (Table 3).

The performed flame temperature analysis allowed a determination of the influence of the injection strategy on the distribution of the flame temperature and the time of occurrence of its given values. The differences in the flame temperature distributions among individual injection strategies have been presented in Fig. 9. The temperature distribution has been presented as a percentage share of a given temperature range that in a given time occupied a specified part of the combustion area.

The fuel injection without fuel dose division and with a division into two parts results in a long time of combustion and an occurrence of areas of high temperaturesl (strategies 1, 2, 3, 4). The temperature of value exceeding 2000 K is maintained until approximately 38 ms after the start of the combustion. An increase in the number of fuel injections causes the areas of higher temperature to occur for a much shorter period of time as opposed to the injection strategy with fewer fuel dose divisions. At the same time as the number of fuel doses increases, the combustion time is reduced (strategies 5 and 7 in Fig. 10). Combustion with higher temperature values (the range of 2000-2600 K) is relatively short (approximately 16 ms) for a fuel dose with a post injection (strategy 4). The percentage share of the area where the highest temperatures occur does not exceed 45% of the area occupied by the flame (the strategies with fuel dose division and those without it).

From the temperature distribution it results that the combustion process ends when in the flame temperature reaches approximately 1500 K. No significantly lower temperatures were observed, which could mean an abrupt ending of the combustion. Similar combustion conditions for liquid fuels were observed by authors of [4].

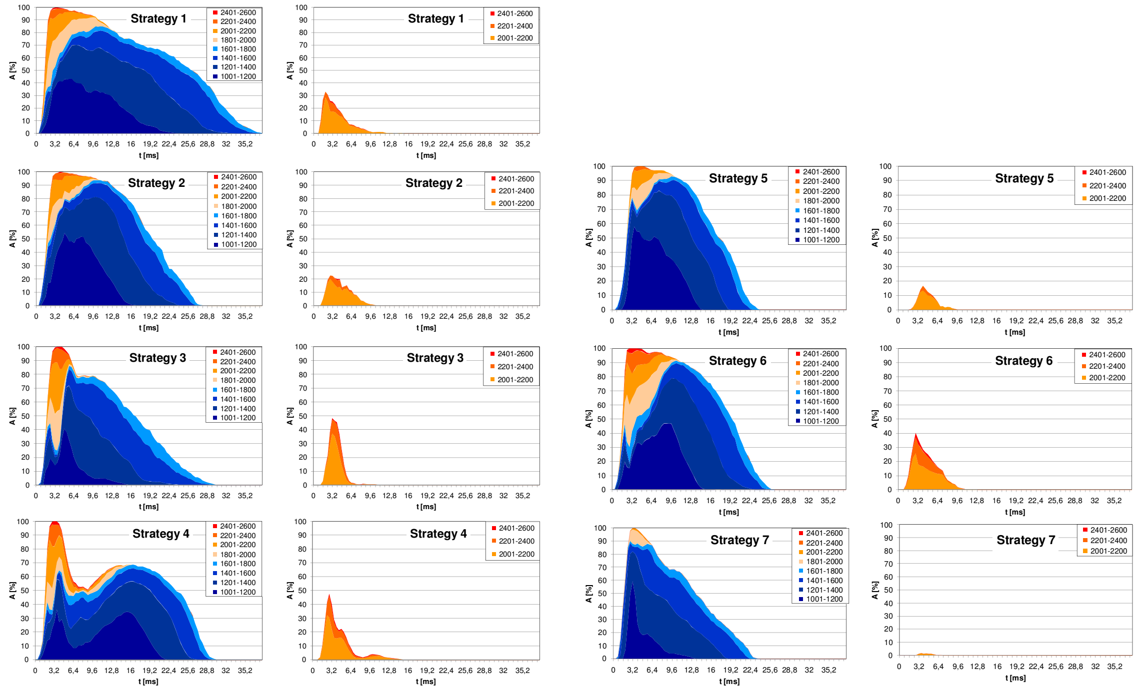


Fig. 9. Flame temperature distribution in the combustion chamber during the process depending on the fuel division strategy

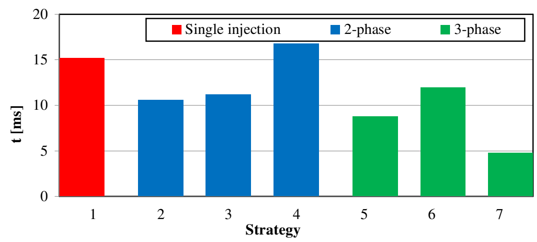


Fig. 10. The comparison of the time of occurrence of the combustion temperatures above 2000 K for different fuel multiple injection control strategies

The analysis of the images allowed a fairly accurate determination of the end of combustion. It has been assumed that the end of combustion shall be the end of the recorded area of flame illumination. Such an assumption allowed a statement that fuel dose division leads to a reduction in the time of combustion (Fig. 10).

6. Conclusions

The investigations of the combustion process in a multiple injected engine allow a complex evaluation of this process in both the macro (average process values) and micro scales (instantaneous values occurring in a given fragment of the combustion chamber). The accuracy of the investigations results from the filming speed and resolution of the recorded images.

The qualitative analysis of the recorded images led to a conclusion that the area occupied by the flame greatly depends on the injection strategy.

It has been observed that in the case of a single fuel dose injection the combustion process is slower than it is in the case of multiple injection. The fuel dose division into three parts at a high pressure injection (strategies 5, 6, 7) results in the shortest time needed for the flame to penetrate the whole combustion chamber and at the same time is characterized by the greatest propagation dynamics, which denotes a growth in the combustion rate. Lower average temperatures of the cycle occur in such a case, which adds to the reduction of the exhaust emissions (nitric oxides in particular).

The selection of the injection strategy allows a control of the combustion process duration. It has been observed that the area occupied by the flame that covers the whole combustion chamber appeared for the shortest time for strategy 5 and the longest time for strategy 1 (no fuel dose division). Besides, in the case of strategy 5 there occurred the greatest dynamics of the flame propagation in the early stage of the combustion. Strategy 1 without fuel dose division and strategies 2, 3 with a fuel dose division into two parts lead to slower flame propagation in the beginning of the combustion process.

The flame propagation velocity heavily depends on the division of the fuel dose or a lack of this division but it does not depend on the number of fuel doses injected before the ignition.

The highest flame front velocities are obtained for the fuel dose division into three parts. This indicates the growth in the combustion rate and better flame propagation, thus better conditions for oxidation and combustion in multiple injection systems.

The performed analysis of the flame temperature allowed a determination of the influence of the fuel injection strategy on the distribution of this temperature and the time of occurrence of its given values.

Fuel injection without fuel dose division and with a fuel dose division into two parts results in a long time of combustion and an occurrence of areas of high temperatures (strategies 1, 2, 3, 4). An increase in the number of fuel doses causes the areas of higher temperature to occur for a much shorter period of time as opposed to the injection strategy with fewer number of fuel doses. At the same time along the increase of the number of fuel doses the combustion time is reduced (strategies 5 and 7).

From the obtained temperature distributions it results that the combustion process fades when the flame temperature lowers to approximately 1500 K. No lower temperatures have been observed, which could confirm a rather abrupt deceleration of the combustion process.

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