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Optical analysis of the gas flame development in a RCM using a high-power ignition system

The combustion process quality is determined by several factors: the composition of the fuel-air mixture in the vicinity of the spark plug and the discharge conditions on the spark plug. This article assesses a high-power ignition system using optical gas flame propagation analyzes. The tests were carried out in a rapid compression machine, using a fast camera for filming. The spark plug discharge quality assessment was determined indirectly by the flame propagation conditions after the ignition of the mixture (during methane combustion). The size of the flame surface and the rate of its change were assumed as a comparative criterion. It has been found that when using an ignition system with high discharge power the rate of flame development is 14% higher with respect to conventional ignition systems. In addition, the shorter development time of the early flame phase after discharge when using the new ignition system was confirmed. Based on the obtained test results and analyzes, modifications of engine operation settings were indicated, resulting from the use of a high discharge power system.

Key words: *spark ignition, plasma ignition, optical tests, combustion process diagnostics, ignition systems*

1. Introduction

The combustion process in a conventional spark-ignition engine is triggered by the external thermal energy generated by the electric arc. Its value and the nature of the transfer of this energy have a fundamental impact on the development of the flame front, and thus on the combustion process parameters (flame development speed, heat release rate, combustion efficiency) and the ability of the mixture to ignite.

There are solutions in the form of an increased number of spark plugs in the combustion chamber (Twin Spark engine or DTSI system – Digital Twin Spark Ignition) to increase the ignition energy and multiply the number of ignition points in the combustion chamber volume. Thanks to these solutions, it is possible to shorten the duration of combustion to a minimum [3, 6]. The disadvantage of this type of ignition systems is the necessity to use a minimum of two spark plugs, which is not always possible due to the space restrictions in the engine head. In addition, such systems have a greater risk of failure.

An alternative method of initiating the ignition using a spark plug discharge is a laser system. It is characterized by the multiple times greater energy supplied and has the capacity of focusing it in a central point of the combustion chamber [9]. In addition, it is possible to ignite the mixture in several points at the same time using one "spark plug". Unfortunately, this system is limited by the large laser costs and the need for frequent repair of optical elements. This results in it being used only in laboratory conditions and prototype engines.

Camilli et al. [2] pointed out the possibility of non-invasive modification of a conventional ignition system using a capacitor system to increase the efficiency of the mixture combustion process. Improved engine performance indicators in the form of specific fuel consumption, power, CO_2 and NO_x emissions, as well as the repeatability of the engine operation cycles. Such a modernized system, in combination with a low-resistance spark plug, allows increasing the efficiency of energy transfer from 1% with a standard solution up to 50% using a system with a larger electrical capacity [7].

The use of capacitors contributes to the increase of the peak current in the breakdown phase reaching a value of up to 1000 A for 5 ns. At the same time, the power released in the system reaches up to 5 MW. A conventional ignition system, with the same engine operating conditions, reaches a value of up to 100 mA, producing 0.125 W of power [8].

Jacobs et al. [4] in collaboration with a certified AVL research center used optical analysis to demonstrate that using a spark plug with increased peak power improves ignition initiation and flame development, resulting in faster combustion of the mixture compared to a conventional spark plug. This is explained by the formation of a large volume plasma between the spark plug electrodes in the first breakdown phase [10].

2. Aim of research

Optical flame development analysis using the ignition systems with a large, impulse delivered maximum power, is limited in the modern literature only to the initial phase of mixture ignition. In addition, it mainly concerns engines powered by a stoichiometric gasoline-air mixture. The current state of knowledge does not allow an unambiguous assessment of the flame development during the combustion of gas mixtures.

The authors of this article proposed the assessment and comparative optical analysis of flame development during the combustion of a stoichiometric mixture of natural gas and air using a conventional ignition system and a system with an increased electrical capacity.

The analysis of the results of such tests will allow to supplement the current state of knowledge with information on the high power maximum ignition system. These works can significantly contribute to improving the combustion process control, and thus obtaining more favorable operational and emission indicators for the operation of spark-ignition engines fueled with natural gas.

3. Research method

3.1. Test object

Experimental research was performed on a rapid compression machine (RCM) that performs a piston cycle of an internal combustion engine at defined thermodynamic conditions. The choice of the test object was dictated by the possibility of full optical access to the combustion chamber (Fig. 1). The RCM technical parameters are shown in Table 1.

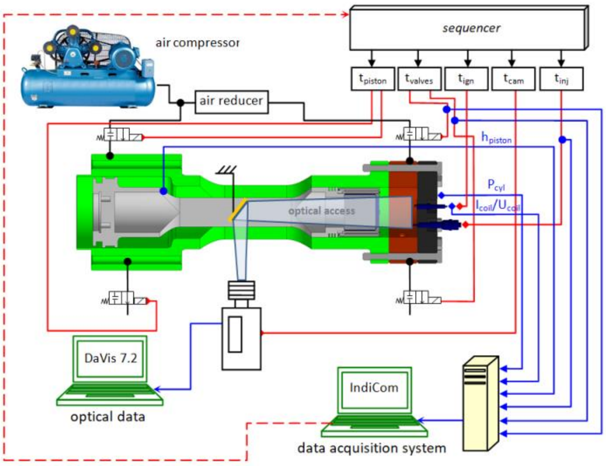

Fig. 1. Diagram of the RCM setup [5]

Table 1. Characteristics of a rapid compression machine

Parameter	Unit	Value
Bore × stroke	mm	80 × 90
Compression ratio	–	14.7
Simulated engine speed	rpm	up to 500
Ignition system	–	spark ignition
Valves system	–	electromagnetic
Fuel system	–	direct gas-injection (electromagnetic injector)
Air system	–	naturally aspirated

The air supply system for the piston enables obtaining the average piston rod linear speed corresponding to the average linear velocity of the piston of the internal combustion engine (at its rotational speed of 500 rpm). Compressed air is supplied to the chamber under the piston rod, which expands the piston rod towards the combustion chamber. The solenoid valves used for controlling the air inlet and exhaust gas outlet in the RCM combustion chamber ensure the required reaction time. The special design of the piston rod in conjunction with a mirror and a transparent piston crown (quartz glass) allows the phenomena occurring in the combustion chamber to be observed.

The natural gas-air mixture is prepared using direct injection with Bosch injectors. It is ignited by a spark plug placed centrally in the combustion chamber. The ignition controller (produced by Mechatronics Kędzia) enables setting the ignition advance angle and the energy discharge value with the specified charging time of the coil. A high-voltage ceramic capacitor connected in parallel was used to execute the high-power ignition (Fig. 2). The order of devices activating along with the time of their activation is controlled by the microcontroller (sequencer) with the trigger uncertainty equal to 1 ns.

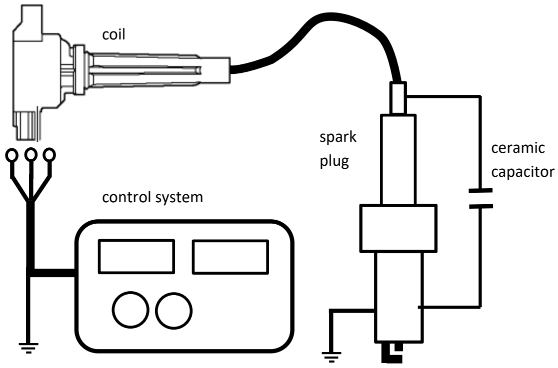

Fig. 2. Setup diagram of a high power ignition system

3.2. Measurement apparatus

To determine the phenomena occurring in the combustion chamber and to compare the ignition systems used, an engine indication system, necessary sensors and a camera for fast filming were used.

A LaVision camera model HSS5 that allows recording images at a maximum frequency of 250,000 Hz was used. The monochrome CMOS sensor used allows to record images at a maximum resolution of 1024 × 1024 pixels. The tests used a 5 kHz filming speed with an image size of 1024 × 624 pixels (the active filming area was 510 × 510 pixels). The camera was controlled by an external computer with the manufacturer's software (DaVis 7.2) allowing advanced image processing.

A piezoelectric AVL GH14D pressure sensor with a measuring range of 0-250 bar was used to record pressure in the RCM combustion chamber. The linear position of the RCM piston was determined using the Megatron LSR 150 ST R5k linear potentiometer. The charging current of the primary ignition coil as well as the discharge voltage on the spark plug was measured using the current clamp (Pico Technology) and the high voltage probe (Chauvin Arnoux SHT40kV), respectively. The above signals were recorded using the induction system – AVL IndiCom with data acquisition software – AVL Concerto.

3.3. Test conditions

A comparison of the proposed methods of spark ignition, i.e. a conventional solution and a high-power ignition required the adoption of a comparative criterion. Thus, the area of the flame in relation to the combustion chamber volume was taken as an indicator. The second indicator used was the flame surface increase rate over time. Due to the method of obtaining research data (access to the combustion chamber from the bottom of the piston – Fig. 1), the flame area is understood as a flat exposure of the image (in contrast to the spatial distribution of the flame in the combustion chamber). Image analysis was performed with 15 repetitions of the combustion process carried out by a rapid compression machine for both ignition systems.

The stoichiometric fuel mixture in the cylinder was determined based on the previously performed characteristics of the injector fuel outflow and the total volume of the

RCM chamber. Before the next cycle, the volume of the cylinder was flushed with fresh air to remove the remaining exhaust gases. The injected gas dose was kept at q_o = 32 mg. The obtained average linear velocity corresponded to the average linear velocity of the piston of an internal combustion engine with the rotational speed equal to n = 360 rpm.

The maximum charging current of the primary winding of the ignition coil ($I_{max\ av}$) was 7 A, which resulted in an average maximum voltage on the secondary winding ($U_{max\ av}$) of 4.3 kV (where the distance between electrodes was d = 0.4 mm). The discharge on the spark plug was on average 10 ms before TDC (t_{av}). The remaining test conditions are shown in Table 2.

Table 2. Test conditions

Ignition type	conventional ignition	high discharge energy ignition
$n_{śr}$ [rpm]	360	
$q_{0\ śr}$ [mg]	32	
$I_{max\ śr}$ [A]	7	
$U_{max\ śr}$ [kV]	4.6	3.9
$t_{śr}$ [ms before TDC]	10.6	9.6
C [pF]	0	480
R [kΩ]	1.6	
d [mm]	0.4	
camera	f = 5 kHz 1024 × 624 px	

4. Data selection criteria

Initial analysis of indicated data, in the form of indicated pressure, showed a high non-repeatability of the RCM work cycles. The issue of the non-repeatability of RCM's work is presented in [1]. The reasons for such operating conditions of RCM are seen in the injection system (injection of gas into the combustion chamber) and the nature of fuel injection.

Further analysis of the cylinder pressure characteristics and the piston position allowed to determine the linear velocity, which was characterized by a very low repeatability between cycles. This was probably due to the instability of the air pressure supplied to the chamber under the piston rod, the limited air tightness of this chamber and the solenoid valves. The linear velocity of the piston, different for each cycle, contributed to the differentiation in the moment of ignition, which was performed as a function of time alone. In addition, each ignition was carried out under different thermodynamic conditions (pressure, temperature) due to different piston positions.

In the next stage of research work, a criterion allowing the elimination of incorrect cycles was adopted. The criterion was the standard deviation of pressure to the time when the combustion took place so that the thermodynamic conditions during the discharge were similar.

Standard deviation values for conventional and high-power ignition were 1.61 and 1.21 bar, respectively (Fig. 3). The pressure characteristics were considered abnormal if their absolute value exceeded the average pressure set for all cycles by 1.21 bar (standard deviation value for high power ignition – see the three-sigma rule). As a result of such criterion, 6 out of 15 cycles for each ignition system were eliminated as unreliable. Standard deviation pressure value for the remaining operating cycles was 0.57 for conventional ignition and 0.83 for ignition with a high maximum discharge power. Differences between mean values of pressure at the moment of ignition for both solutions including selected cycles did not exceed 8%.

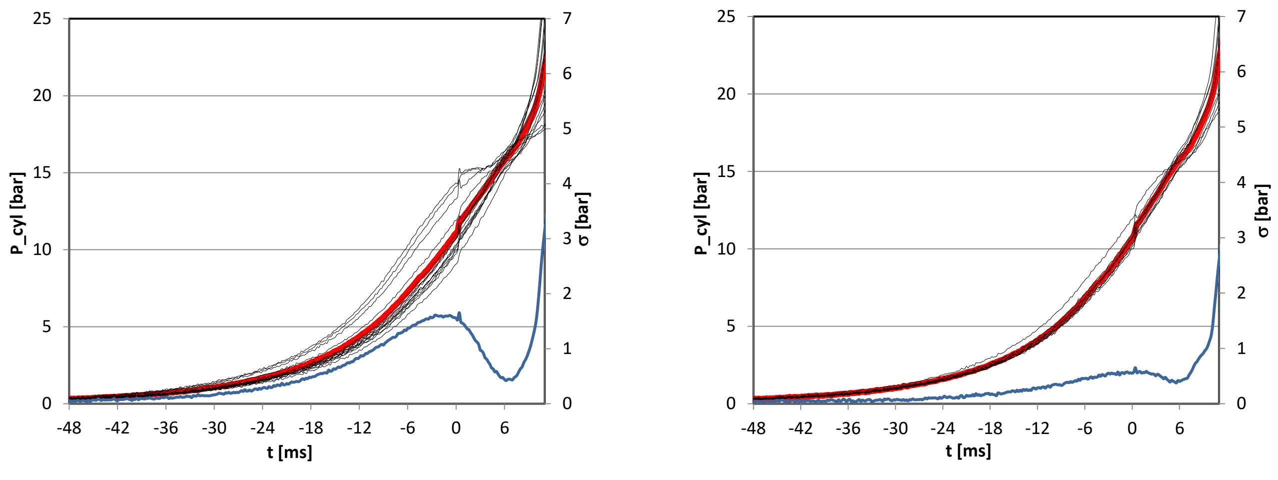

Fig. 3. Sequences of indicated pressure P_cyl (black), mean value (red) and standard deviation (blue) for the compression curve using conventional ignition. On the left before the selection, on the right after the exclusion of incorrect RCM work cycles; the characteristic peak on the pressure curve was caused by interferences from the ignition system (t = 0 ms)

5. Optical analysis algorithms

Pictures taken using the HSS5 camera included more than 140 ms of the RCM work cycle at 5000 fps. Such a long recording time resulted from the uncertainty of the moment of ignition. In order to achieve the desired results, further processing of the photos was necessary. For this purpose, the camera manufacturer software LaVision – DaVis 7.2 was used. The algorithm for optical analysis is shown in Fig. 4.

In the first stage, the number of photos was limited to the minimum value, containing only the necessary information. The analysis was limited to approximately 300 consecutive images. Then, the background was subtracted (the so-called reference image – a black frame). This procedure was used to eliminate noises and reflections on other pictures.

In the next stage, a mask was used to limit the analyzed area. The circle-shaped mask was the same size as the combustion chamber and insulated the remaining area outside the chamber (the bottom of the piston, cylinder walls).

The last stage of the analysis was to calculate the flame area in the RCM combustion chamber. A program was written in the internal language of the DaVis software by the article authors. For its operation it was necessary to:

1) determine the minimum luminance value attributed to the analyzed pixel (above the given luminance value the pixel was treated as the flame surface);

2) determine the cylinder diameter expressed in pixels.

Images showing the beginning of an electric discharge with different discharge powers are shown in Fig. 5.

The image sequences processed using the algorithm shown in Figure 4 are depicted in Fig. 6.

The obtained values of the flame surface and their analysis are presented in Chapter 6.

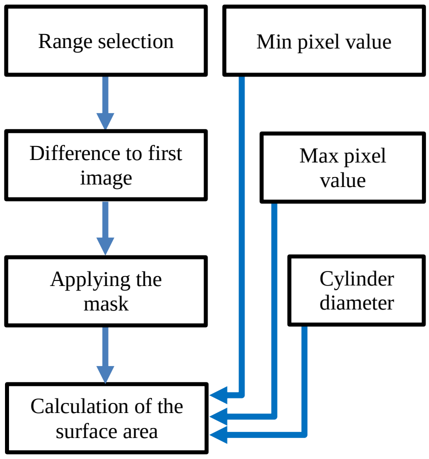

Fig. 4. Optical analysis algorithm using DaVis 7.2

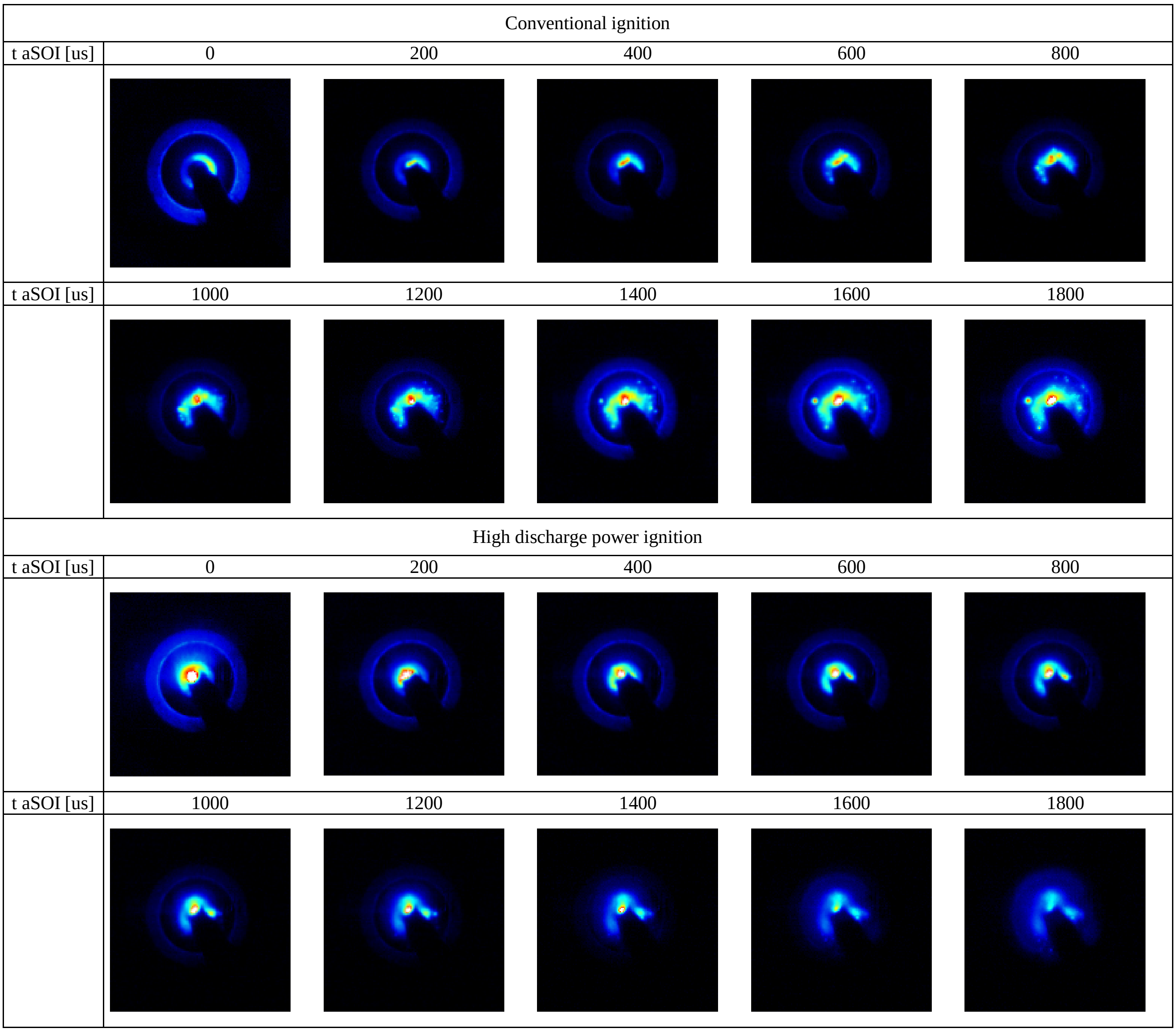

Fig. 5. Images of the ignition phase start (f = 5 kHz, the first image represents SOI – start of ignition)

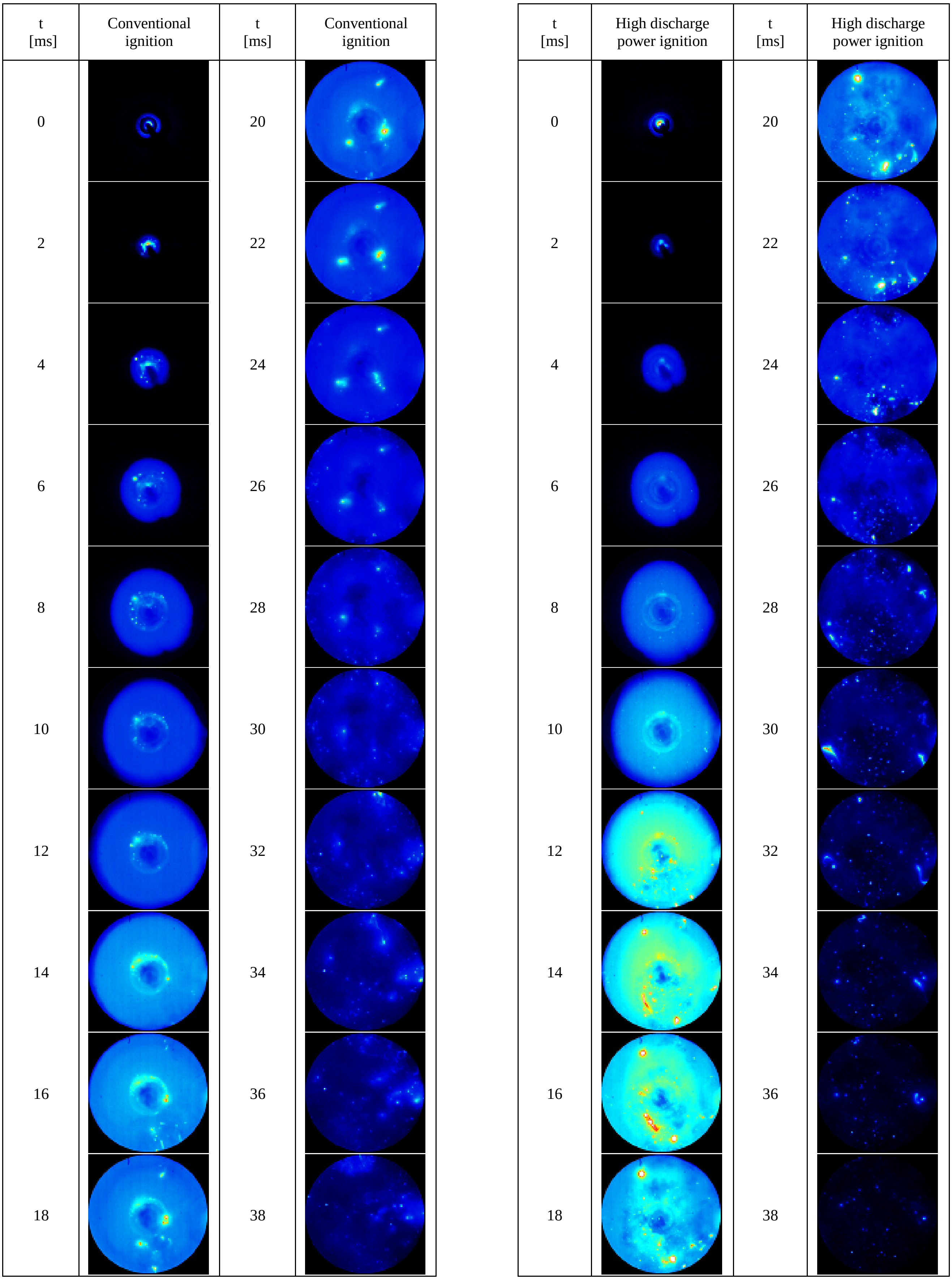

Fig. 6. Selected images of the combustion process using conventional ignition and high discharge power ignition (f = 5 kHz, the first image represents SOI – start of ignition)

6. Results

The flame area values in the RCM combustion chamber were determined as a result of image analysis using the DaVis software. The specific nature of the optical access to the combustion chamber and the software application of image masking made it possible to analyze over 1800 mm^2 of the filmed combustion chamber area. The results of analyzes of all selected cycles along with the standard deviation value are shown in Fig. 7. The moment of the electric discharge between the spark plugs was taken as the point where time = 0.

Standard deviation values of the surface area in the flame development phase (up to 10 ms) and in the decay phase (from 25 ms) for conventional ignition exceed the values of this deviation when using a high-capacity ignition. Alternative ignition is characterized by greater stability and process repeatability, which is probably due to the higher value of current flowing in the breakdown phase, in which the ignition is initiated. In the case of a conventional solution, the ignition may be initiated at random during one of three stages of ignition: breakdown, arc or glow. In addition, a shorter time gap is observed between breakdown point and the development of the flame (Fig. 8) with a mixture ignited with high power ignition. The greater flame surface area value in the combustion chamber using conventional ignition in the first period after the start of the process (up to 2 ms) result from the constraints of the created program. The high luminance value attributed to the pixels at the time of the electric breakdown was treated as the flame surface. Although, in reality the higher brightness (luminance of pixels) was caused by the visible light emitted by the electric arc. Nevertheless, on Fig. 8, it is possible to notice a greater emission of visible light during a standard ignition, which causes additional energy losses in the system.

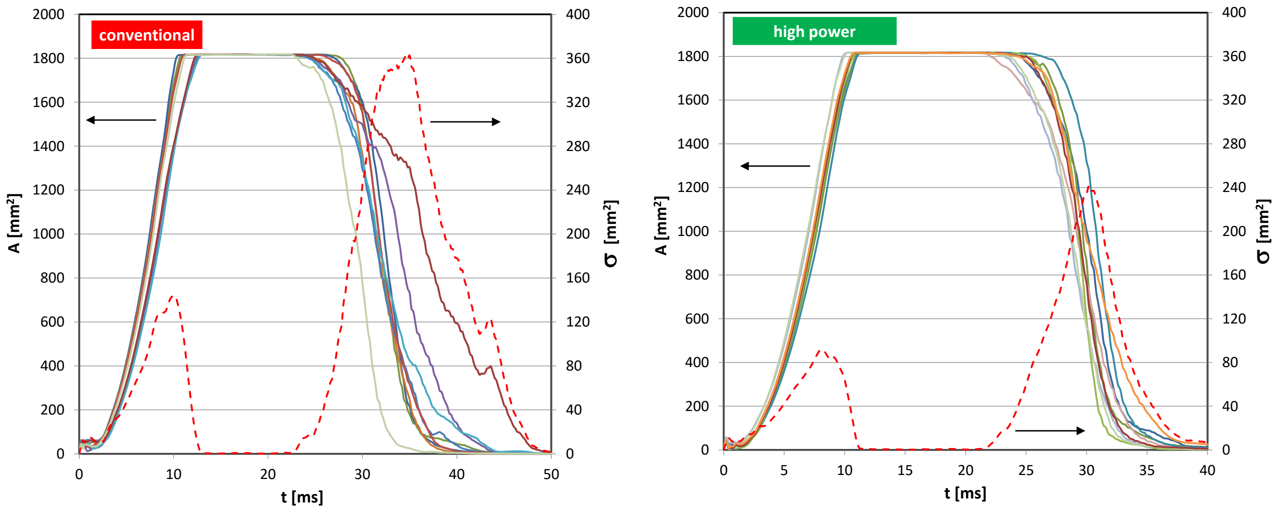

Fig. 7. Flame surface area as a function of time (solid line) and its standard deviation (dashed line); on the left – conventional ignition, on the right – high-power ignition

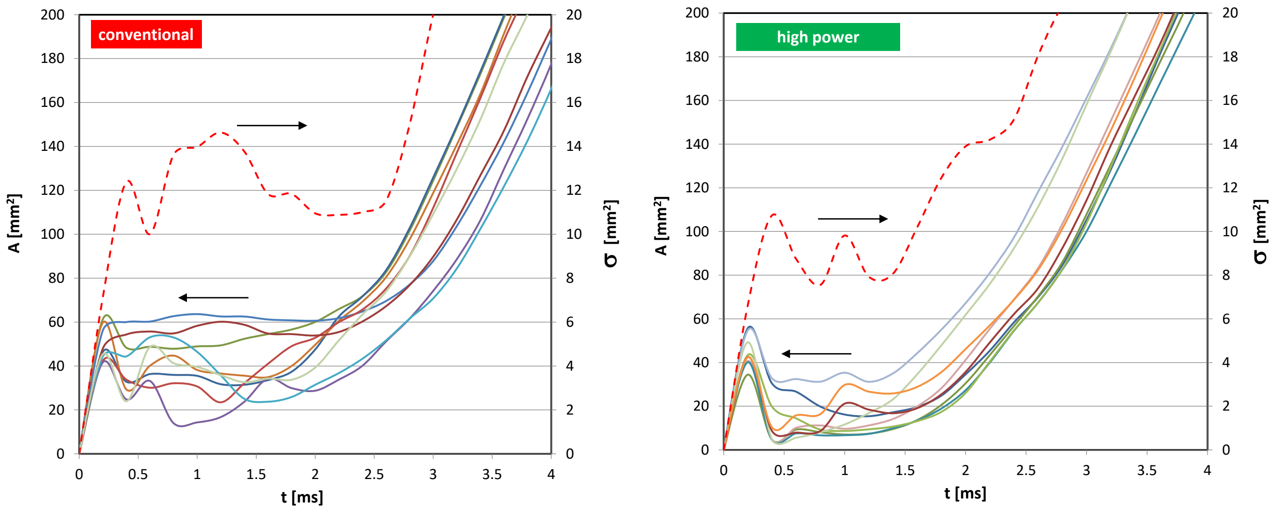

Fig. 8. Flame surface area as a function of time (solid line) and its standard deviation (dashed line) for the early stage of flame development; on the left - conventional ignition, on the right - high-power ignition

The mean values of the flame surface area and the time derivative of this field inform indirectly about the flame development rate. The results of these analyzes are presented in Fig. 9. From the mean value analyzes it was found, that the flame presence duration in the combustion chamber for high-power ignition was reduced by about 20% in relation to the conventional ignition. In addition, the maximum flame velocity, expressed as a derivative of the surface area of the flame, was found to be 14% higher. These values indicate the possibility of increasing the thermal efficiency of the engine using a high-power ignition.

The analysis of the initial flame development phase in a short time after the electric breakdown allowed to determine the average time delay from the electric breakdown to the moment when the flame front begins developing. This time was approximately 2 ms for standard ignition and 1.5 ms for high-power ignition. These values are directly referenced in the voltage values on the secondary winding of the ignition coil, where the voltage value after this time drops to zero, thus ending the glow stage in the discharge process. With regard to the second solution, its use in an internal combustion engine may require correction of the ignition advance angle.

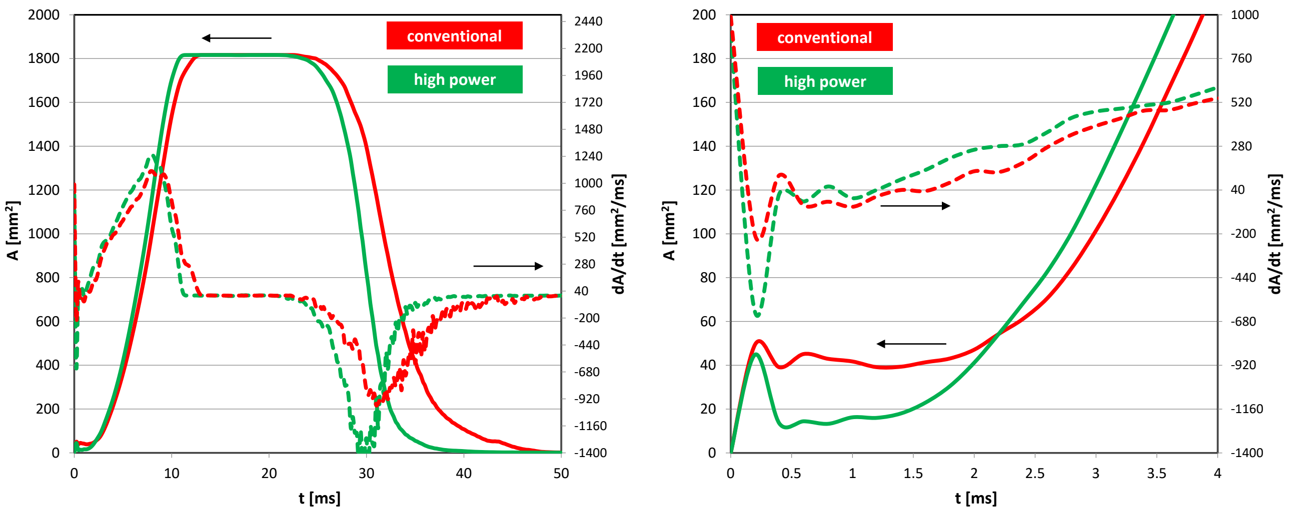

Fig. 9. Average flame area in the combustion chamber as a function of time (solid line) and its derivative (dashed line) for the entire combustion process (left), and early stage of flame development (right)

7. Conclusions

The analysis presented in the article concerned the optical evaluation of flame development using two ignition methods: conventional and high discharge power, when burning gaseous fuel (methane) using a stoichiometric mixture.

Based on the specific comparative criteria, which were: the flame surface area and its rate of change, the following conclusions were formulated for ignition systems (classical and high ignition power):

1. Based on the mean values analysis of the flame surface averaged over many cycles, the flame duration in the combustion chamber was found to be reduced by about 20% when using high-power ignition relative to the conventional ignition.
2. The maximum flame velocity expressed as a derivative of the surface area of the flame was determined to be approximately 14% greater.
3. During the analysis of the initial flame development phase, the average time delay between the electric breakdown and the development of the flame front was determined (the value of the secondary voltage in the system was used as a confirmation). This time was approximately 2 ms for standard ignition and 1.5 ms for high-power ignition.

The values indicated above show the possibility of increasing the thermal efficiency of the engine with the use of a high-capacity ignition.

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Nomenclature

A	flame area
f	frequency
RCM	rapid compression machine
P_cyl	cylinder indicating pressure
σ	standard deviation
t	time
SOI	start of ignition
U	voltage
I	current
q_o	fuel dose
n	engine speed
TDC	top dead centre
DTSI	Digital Twin Spark Ignition

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