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Experimental identification of the electrical discharge on a surface gap spark plug

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The main objective of the research is to assess the influence of the spark plug electrodes geometry on the structure of the electric arc. This issue is increasingly important in modern gas-fueled engines with lean and stratified air-gas mixtures. To explain the influence of electrode geometry on selected spark discharge indicators, optical tests were conducted, and the parameters of the test history, together with the movies of the discharging process, were recorded and analyzed. The tests were carried out comparatively for two types of spark plugs on the test stand: conventional spark plug and spark plug with a flat ground electrode. It has been found that using flat plug electrodes allows a larger spark area covered by the electric arc without losing the intensity of radiation. More, using an unconventional spark plug results in a shorter discharge time relative to the conventional spark plug, while the geometry of the conventional spark plug allows for maintaining a stable electric arc with a minimum tendency for creeping.

Key words: *spark discharge, spark plug geometry, ignition system, optical research, electric arc development*

1. Introduction

The development of onboard energy sources in vehicles aims to complete or significantly eliminate exhaust emissions [12, 16]. Work in this area involves improving combustion engines or implementing battery and fuel cell systems [10, 13]. According to information reported by Grand View Research, the internal combustion engine market in 2021 consisted of almost 170 million units and a growth trend of 9.3% by 2030 is predicted [9].

The internal combustion engine is a thermal machine that can be powered by fuels of very different composition and physical state, which makes it a multipurpose source of mechanical energy. The combustion of various types of gaseous fuels in internal combustion engines has positive effects on the environmental performance of the power unit and, by burning mixtures with high excess air in addition to improving environmental performance, a reduction in fuel consumption as a result of increased thermal efficiency [7].

As the excess air in the combustible mixture increases, the demand for energy for initiating the combustion process rises [11]. To increase the ignition energy in SI engines and thus improve the benefits of lean combustion, the development of modern alternative ignition systems such as laser ignition, Microwave-Assisted Spark Ignition, Radio Frequency Based Corona Ignition system or the use of a pre-combustion chamber is being carried out [18]. Studies using a Rapid Compression Machine for three configurations of the system using a pre-combustion chamber indicated a significant improvement in thermodynamic indicators and flame development under lean natural gas combustion conditions relative to a conventional SI system [4]. A limitation in using the mentioned systems is their complication and, at the moment, the fact that they are not implemented on a wide scale.

In order to improve ignition properties, it is possible to modify the widely used spark ignition, that is, the initialization of the combustion process from an electric arc. An example is Digital Twin Spark Ignition [14]. Positive results were achieved by modifying the ignition system by implementing capacitors, which resulted in increased engine stability, shortened combustion duration CA10-90, reduced emissions and fuel consumption [5]. Fiedkiewicz et al. [12] also conducted work on increasing the energy generated by a spark ignition system by using a high-voltage ceramic capacitor connected in parallel. As a result, optical and indicator tests on rapid compression machine showed a 20% reduction in combustion time and a 14% increase in flame propagation speed. Hayashi et al. [8] pointed out the possibility of improving charge ignitability by controlling the discharge current. When the intensity of charge movement is high, the discharge current should be shortened, and when it is low, it should be lengthened. As a result, it is possible to increase the limiting excess ratio by 0.2, up-to 1.8.

During engine testing, the effect of the ground electrode number on engine operation was evaluated [1]. Of the spark plugs with four, two, one and no external ground electrodes, the best results in the most stable engine operation were achieved with a plug without a side ground electrode. Another study [3] compared a conventional spark plug and one equipped with a corona ground electrode. The corona spark plug improved fuel economy and reduced hydrocarbon emissions with an undesirable increase in nitrogen oxide emissions.

Tambasco at al. [17] investigated the comparative evaluation of spark plugs with a J-shaped ground electrode and a four-electrode spark plug with flat electrodes. The research was conducted using a small constant volume chamber. Higher thermal energy and energy conversion efficiency from electricity to heat were obtained for the J-shaped electrode plug. In addition to the number of electrodes, the gap between the ground and central electrodes is also important. Optical and thermodynamic tests under different excess air ratio conditions for plugs with gaps of 1.0, 1.2 and 1.4 showed the effect of the gap on combustion, especially under stoichiometric and lean combustion conditions [2]. The worst results in terms of engine stability were obtained with a spark plug using a 1 mm gap. Energy and emission benefits increased as the gap between electrodes widened.

A simulation study comparing the effects of using an iridium spark plug with a center electrode diameter of 0.7 mm and one with a center electrode diameter of 2.5 mm showed an improvement in combustion stability of a maximum by 13.5% at partial load and low speed [15]. In addition, the possibility of reducing fuel consumption by 1.25% was indicated.

In consideration of the literature information regarding the possibility of increasing ignition energy by changing the geometry of the spark plug, the authors of this article attempted a comparative evaluation of two types of spark plugs. It was decided to answer the question of what effect the shape of the spark plug electrodes has on the discharge waveform and efficiency. It was resolved to conduct model tests using high-speed imaging and recording of electrical parameters. Two spark plugs differing in the shape of the ground electrode, and the material of the central electrode were selected for the study. The authors hypothesize that the model results correlate with the possibility of improving the combustion process in gas engines operating in lean combustion mode. In the mentioned mode of operation, ignition energy is particularly important and determines the final performance and emissions of the engine.

2. Methodology

2.1. Spark plugs geometry

The test objects accepted for investigations were two spark plugs (Fig. 1) differing in the electrodes' geometry and the central electrode's material. The first (Fig. 1a), recognized as conventional due to its wide use in SI internal combustion engines, is a spark plug with a side electrode with a truncated cone, whose central electrode is made of iridium, and the gap between the electrodes is 0.8 mm. The other one (Fig. 1b) is a spark plug with a flat side electrode that realizes a semi-surface discharge, whose central electrode is made of nickel, and the gap between the electrodes is 1.3 mm. For this paper, the conventional spark plug is designated by Z, while the spark plug with a flat ground electrode is R. Both plugs have M10 threads so that they can be used in two-stage combustion systems of high-speed engines with limited space.

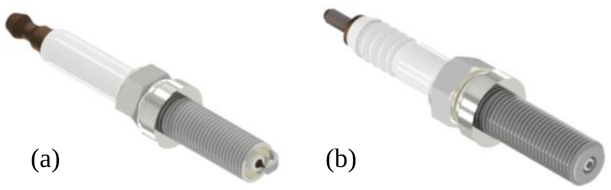

Fig. 1. Spark plug units used during testing: (a) a conventional Z spark plug and (b) a spark plug with a flat ground electrode R

2.2. Test stand and investigating apparatus

To evaluate the effect of spark plug geometry on the discharge character, a test stand fitted with a constant-volume chamber, high-speed filming equipment and electrical measurement apparatus was used (Fig. 2).

The constant volume chamber used, in which the spark plugs were installed, has a capacity of 2.2 L and optical access through 5 quartz glasses with a thickness of 30 mm. Attached to the chamber is an air pumping system consisting of a compressor, cylinder and solenoid valves. LaVision's HSS5 high-speed recording camera, an AF Nikkor prime lens, and a 700FS80-50 filter were used for optical signal recording. Electrical parameters were recorded with an eight-channel Sirius data acquisition system from DEWESoft with a maximum sampling rate of 200 kHz and voltages of 200 V and 1200 V (four channels each). Current clamp meter PP218 was used for current measurement, and capacitive pickup probe PP178 for high voltage. The voltage on the primary side was recorded directly.

A controller from the mechatronics company was used to check the ignition coil with the possibility of controlling the ignition timing and the coil charging time (up to 5 ms). A sequencer was used to initiate the operation of the camera and the ignition controller, allowing the start of the devices to be controlled with an accuracy of 1 ns.

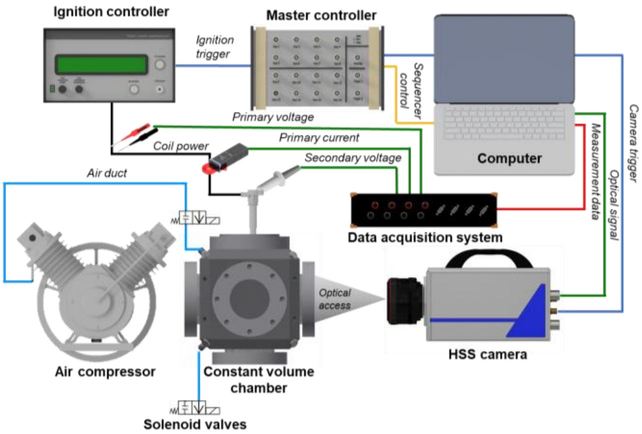

Fig. 2. Layout of test stand used to identify spark discharge

2.3. Experimental setup

The design of the spark plugs required different locations in the constant-volume chamber so that the direction of recording would remain constant and the optical system would not be affected during testing. Spark plug Z was placed in the axis of the chamber perpendicular to the direction of the camera lens so that the discharge could be recorded from the side (Fig. 3a). Spark plug R, on the other hand, was placed in the rear of the chamber in the axis of the lens to register the image from the front (Fig. 3b). During testing, the camera was moved back or forward by the difference in distance between the spark plugs as required.

The optical test plan included recording the discharge for ambient pressure and two overpressure values of 5 and 8 bar. During electrical measurements, a test point was added for 12 bar overpressure. The tests were conducted for a 4 ms constant value of the ignition coil charging time, leading to an end-charge current of 10.0 A.

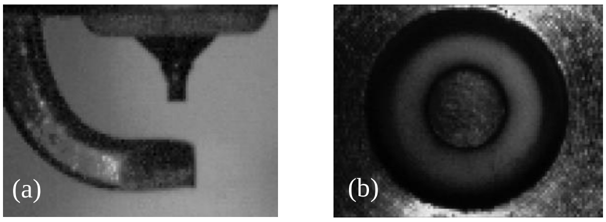

Fig. 3. View of spark plug Z from the side (a) and R from the front (b) when the discharge process is recorded optically

3. Results

3.1. Optical observations

The spark discharge at the electrodes of the analyzed spark plugs was recorded at 100,000 fps with a resolution of 128 × 80 pixels (Fig. 4-5). Due to the intensity of the discharge, an additional 700FS80-50 filter was put on the lens, and the exposure time was reduced significantly. DaVis software was used to process the images, allowing the background to be removed and the images to be parameterized to determine the intensity of the luminous and the area of the electric arc.

Figure 4 shows the first 40 μs of the spark discharge at ambient pressure in the chamber and an ignition coil charging time of 4 ms. In addition to the view of the arc, the electrode contours in the white line have been added. The first photo making the arc visible is marked as time 0. Luminous intensity is illustrated as a blue-to-red spectrum corresponding to the arc temperature, while the accurate value was not determined. In the case of the R spark plug, the arc is between the center and ground electrodes perpendicular to the axis of the spark plug, whereas in the case of the Z plug, the location is parallel. For the Z spark plug, a high concentration of energy was noted at the tip of the central electrode, which was not found for the R spark plug. However, this is probably related to the properties of the materials used for the electrodes. For the R spark plug, with time, the heat spreads over the surface of the central electrode without an expressed increase in heat density.

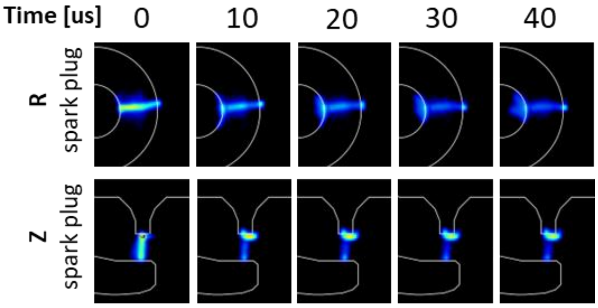

Fig. 4. Sequence of electric arc images without back pressure in a constant volume chamber

The effects of increasing the chamber pressure to 8 bar for the same ignition coil charging time are shown in Fig. 5. For this case, the sequence of images begins at 20 μs from the arc breakdown. The first two images were omitted because the luminescence intensity was too high, which led to their overexposure. In both cases, the area of the arc has increased, and the shape has changed. At the ends of the arcs, one can see a marked concentration of energy in both cases, with a longer duration for the R spark plug. The location of the arc for the R spark plug has changed relative to the position in Fig. 4. This type of geometry changes the arc's location within the electrodes from cycle to cycle, which is visible when analyzing several consecutive discharges. When the recording of the full discharge is analyzed, the change in arc location can also be seen within a cycle.

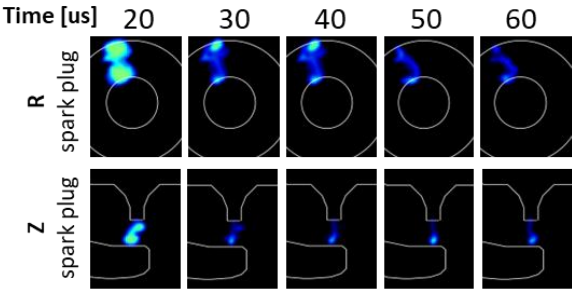

Fig. 5. Sequence of electric arc images with back pressure in a constant volume chamber of 8 bar

The previously presented images were further processed to determine the area and luminous intensity of the electric arc. In addition, the case of a 5 bar chamber pressure was also analyzed. Figure 6 shows the change in arc area for three values of pressure and both spark plugs. In all analyzed cases, the arc generated by the R spark plug has a larger surface area, and the differences range from 89 to as much as twice. The R spark plug is more responsive to pressure changes considering the surface area. In the case of the Z spark plug for different pressure values, the results are comparable.

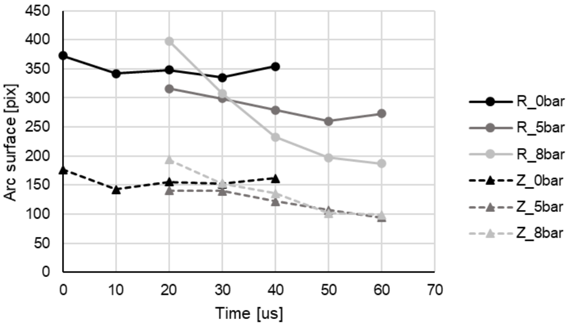

Fig. 6. Effect of pressure in the constant volume chamber on the electric arc area generated by the analyzed spark plugs

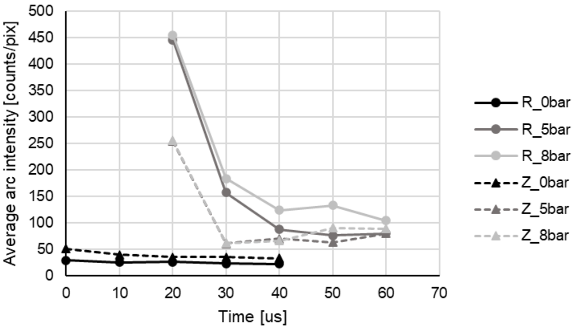

Fig. 7. Effect of pressure in the constant volume chamber on the average luminescence of the electric arc generated by the analyzed spark plugs

Each recorded pixel has a value representing the glow intensity in the range of 0 to 1023. Based on the number of pixels representing the arc area and the intensity value of each pixel, the average glow intensity of the arc was determined. For ambient pressure, a higher value of the average glow intensity was achieved with spark plug Z. As the pressure and, thus, the air density increases, the average glow intensity increases. For higher pressure values in the initial stage of arc glowing, the R spark plug turns out to be better, and the differences range from 17% to as much as twice.

A parameter that has also been considered is the maximum illumination value for a particular image (Fig. 8). The maximum possible value is reached for overpressure values of 5 and 8 bar, considering the optics used. The trends correspond to those shown in the previous Fig. 7.

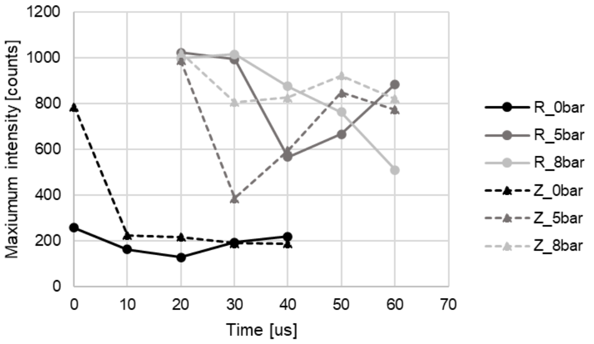

Fig. 8. Effect of pressure in the constant volume chamber on the maximum luminescence of the electric arc generated by the analyzed spark plugs

3.2. Electrical measurements

To complement the optical tests, electrical measurements were conducted. During the discharge, the voltage and current in the primary circuit and the voltage in the secondary circuit of the ignition coil were recorded (Fig. 9). For an ignition coil charging time of 4 ms, the amount of energy delivered is about 242 mJ. The energy transferred to the plug is minus the coil losses. Because the tests were conducted in a model way without combustion, the waveforms differ slightly from those obtained on a real internal combustion engine.

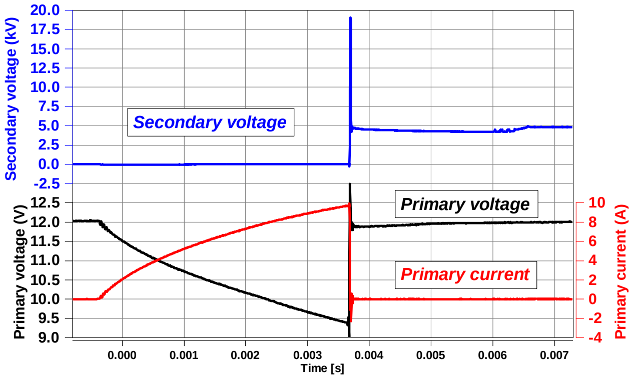

Fig. 9. History of measured electrical parameters during the process of charging the ignition coil and spark discharge

Figure 10 shows an example of the high voltage waveform in the secondary circuit of the ignition coil for an R and Z plug at 5 bar. The waveform for an R-type plug (red) during the entire discharge phase is less regular. This indicates a change in the position of the arc or, in extreme situations, an interruption. The Z spark plug is characterized by generating a more stable arc with localized interference, particularly evident at the end of the discharge. An important piece of information to obtain an explanation for the larger area of the arc and slightly higher intensity of the arc for the R spark plug relative to the Z spark plug is the duration of the discharge. For the illustrated single case, the discharge generated by the R spark plug is shorter by 0.86 ms, 70.6% of the discharge time on the Z spark plug.

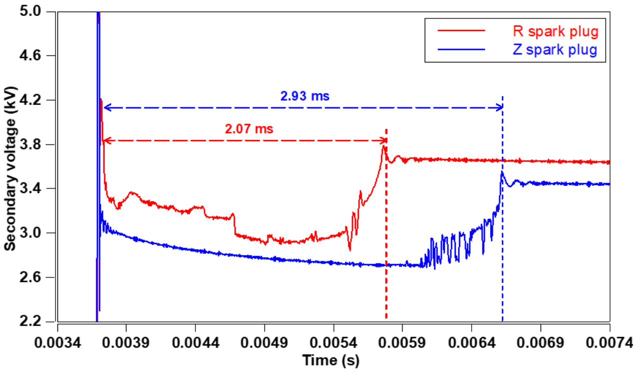

Fig. 10. High voltage waveform in the secondary circuit of the ignition coil during a spark discharge with the discharge time specified

Figure 11 shows the discharge duration relative to chamber pressure for the two spark plugs analyzed. The data shown in the diagram (Fig. 11) are averaged from five consecutive discharges at a distance of 120 ms, corresponding to 1000 rpm of a four-stroke engine speed. In the overpressure area, the discharge time decreases as the pressure increases. Throughout the analyzed area, the spark plug Z generates a discharge that lasts 4 to 30% longer. As a result of the reduction in discharge time, while supplying the same energy to the ignition coil, the physical arc breakdown processes increase in intensity. As a result, the change in the geometry of the spark plug electrodes caused an improvement in the energy density of the discharge.

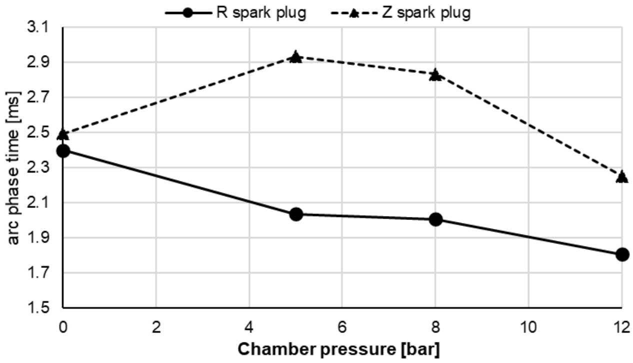

Fig. 11. Dependence of spark discharge duration on pressure in constant volume chamber

4. Conclusion

In the study presented in this paper, a model experimental study was performed to evaluate the effect of spark plug geometry on spark discharge. The tests were carried out using a constant-volume chamber, which allowed a partial reconstruction the conditions in the cylinder of an internal combustion engine. The effect of the discharge was evaluated at an ignition coil constant charging time value and a variable value of the overpressure in the Constant

Volume Chamber. According to the images of the spark discharge taken by high-speed imaging techniques and the recording of the voltage and current history of the ignition coil circuits, the following conclusions have been made:

- high luminous intensity of the spark discharge process during filming requires changes in the optical setup for the various phases of the discharge (appropriate filters, exposure time);
- surrounding pressure significantly affects the nature of the discharge, which becomes more intense as the pressure increases;
- the geometry of the spark plug significantly impacts the discharge pattern. For a conventional spark plug, the position of the arc during the discharge does not significantly change relative to the electrodes, in contrast to a plug with a flat electrode under conditions without air movement;
- using an R-type spark plug with a flat ground electrode makes it possible to increase the area of the arc while maintaining the intensity of the illumination;
- type R spark plug with a flat ground electrode is characterized by a shortening of the spark discharge leading to an increase in the concentration of energy in the electric arc which can contribute to an increase in combustion efficiency under unfavorable conditions inside the ignition chamber of a gas engines.

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