Optical study on spark plug discharge in the two-stage combustion system in terms of prechamber-specific charge motion

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Abstract

Lean-burn combustion systems applied in I.C. engines provide higher thermal efficiency than rich-burn combustion systems. However, in the case of highly diluted mixtures, especially mixtures of alternative gaseous fuels with air, a significantly bigger portion of the energy is required to initiate the combustion process. For that purpose spark-jet ignition systems providing enhanced ignitability could be applied. The use of divided combustion chambers and injection of additional fuel quantity to the ignition chamber reduces air excess and therefore demand on energy to ignite the mixture. This type of scavenging, in combination with charge transfer from the main chamber, induces charge movement complexity in the regions close to the spark plug gap and can also negatively influence the spark plug discharge, which initiates the pre-combustion process. The distortions of spark kernel can result in misfiring, inadmissible in terms of its harmful environmental impact. The aim of this study was to examine the impact of charge motion in the ignition chamber on spark plug discharge initiating pre-combustion. An indication of its distortions is critical to the identification of misfiring source and adjustment of control parameters in such an ignition system.

The spark plug discharge has been recorded with high-speed CMOS camera LaVision HSS5 with registration frequency of 140/30 kHz, depending on the discharge phase. High voltage was generated by ignition coil triggered with ignition control system adjusted to provide a variable time period of its charging and therefore vary the released energy. Two opposite flow directions, corresponding to different positions of the spark plug, have been examined. The different velocities of charge flowing through the spark gap have been applied. Recorded images have been processed in LaVision Davis and Fiji ImageJ software.

In the measurement course, the positive correlation between the character of charge movement and direction of fuel jet development has been confirmed. The influence of energy stored in the capacitance of the ignition system on the morphology of spark plug discharge has been noticed. The higher energy of the discharge causes bigger luminescence of spark kernel. The increased velocity of span air flowing through the spark gap causes a shift of ionized centers and, in consequence, reduced spark luminescence intensity and its deformation. It has been confirmed that the position of the spark plug in the spark-jet ignition system should be adjusted regarding the direction of charge swirling to avoid breaking the spark kernel.

Keywords: Spark-jet ignition, prechamber, spark plug, spark plug gap, discharge kernel

1. Introduction

The on-ignition robustness is one of the key issues in the further development of spark ignition (SI) engines, especially these operated with lean charges. Combustion of such mixtures, despite inadmissibly higher cycle thermal efficiency and lower NOx emission, indicates bigger demand for ignition energy due to the reduced fuel concentration in the mixture. Bigger ignition energy and therefore ignition capability can be achieved using the spark-jet ignition system (Fig. 1).

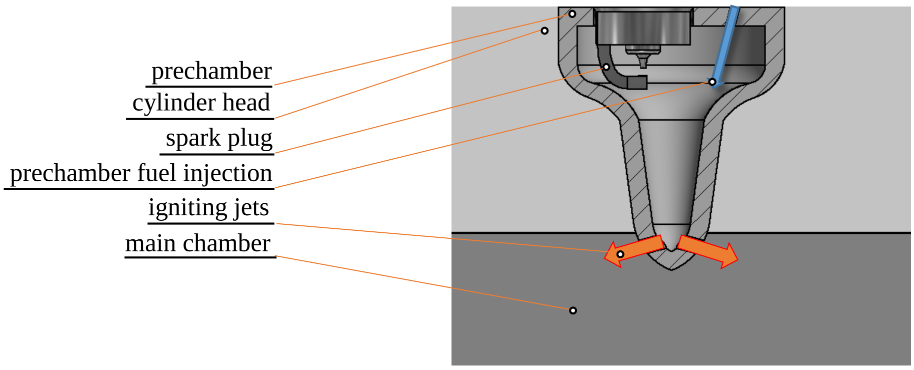

Fig. 1. Spark-jet ignition

Spark-jet ignition (named also turbulent jet ignition, TJI) consists additional ignition chamber (prechamber), possibly with fuel supply (scavenged variant) and the spark plug mounted on the prechambers top. The operation of TJI starts with pre-combustion initiated with conventional spark ignition. In the result of pre-combustion event, igniting jets transfer into the main combustion chamber providing the start of the main combustion process.
In relation to the primary ignition, the spark energy is typically calculated based on the voltage (U) and current (I) signals:

$$E = \int_0^t U(t)I(t)dt$$

The voltage and current indicate the following courses in connection to the discharge phases (Fig. 2):

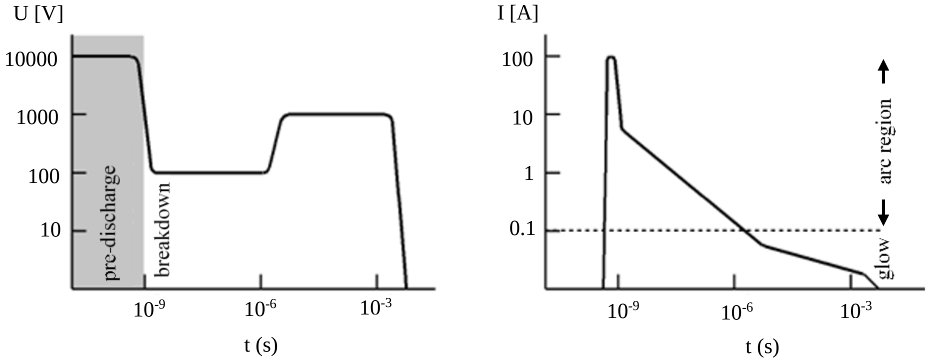

Fig. 2. Voltage and current in spark plug discharge [1]

The first phase is high voltage pre-discharge indicating initially no current. In this stage medium contained in the spark plug gap is being ionized. As this study continues the authorship investigations on mixture formation in CNG combustion system [2], the ionization issue will be particularly explained– with respect to the fuel type. The ionization degree describes the Eggert-Saha equation:

$$\frac{n_i^2}{n_a} = \frac{2\sqrt{(2\cdot\pi\cdot m_e\cdot k\cdot T)^3}}{h^3} exp\left(-\frac{E_i}{k\cdot T}\right)$$

where:

- n_i– number of ionized molecules,
- n_a– total number of moles,
- m_e– electron mass ($9.109\cdot10^{-31}$ kg),
- k– Boltzmann's constant ($1.38\cdot10^{-23}$ [J/K]),
- T– temperature [K],
- h– Planck's constant ($6.6256\cdot10^{-34}$ [J·s]),
- E_i– substance's ionization energy [eV].

The ionization energy is highly dependent on the mediums composition (characterized by E_i). When considering the engine combustion, the energy necessary to ionize the gasoline-air mixture is significantly smaller than the energy needed to the CNG-air mixture ionization [3]. Further, regarding the Eggert-Saha equation, under the assumed conditions, the CNG-air mixtures tend to be worse ionized at the defined time instances, generating additional demand to the ignition system. In the arcing phase, an intensive optical signal is being generated, then the shock wave appears in the electrode gap volume and the spark kernel grows. In the early stage of spark kernel growth, the shock wave develops correspondingly to the power law [4], induces the flow field following the spark and is transferred out from the high pressure and temperature discharge channel [5]. The heat transfer in this channel and its temperature are influenced by the electrode geometry and effects flame formation. Next stage is the glowing, influenced by conditions in the electrodes gap [6]. In general, spark peak voltage increases near linear with an increase in pressure and temperature reduction. The experiments on implementation of a low-voltage system to ignite the mixtures have been conducted by Uber et al [7] and indicate positive potential in arc generation, which however needs to be analyzed in terms of the inflammation capability.

Also, the flow field impacts kernel evolution [8]. In the investigated flow-channel (stream velocity 33 m/s and 5% turbulence level), the transfer of high-temperature plasma downstream the flow has been noted.

As mentioned, the robust on-ignition event is crucial in the further development of combustion engines. Insufficient energy transferred to the mixture results in misfiring, which is inadmissible due to its consequences as increased exhaust emissions [9]. It is stated, that even 1% of misfires causes significantly increased emission of the unburned hydrocarbons.

The spark ignition is one of the known methods to initiate the combustion process. Nevertheless, among other ignition systems, spark ignition indicates beneficial properties in terms of its efficiency, comparing to the laser-based ignition. The investigations conducted using constant volume chamber deliver, that higher ignition energy is required, when using laser, due to the losses on the quartz glass providing the transfer of ignition energy to the combustion chamber [10].

The minimum ignition energy (MIE) changes with pressure and temperature [6, 11]. The dependency for lean laminar MIE has been described as follows:

$$MIE_L \sim p^{-0.8}$$

and positively verified.

The sparking characteristic depends on some ignition parameters (charging time) and electrode gap distance [12]. In the cited study effect of these two parameters on the sparking course and on the inflammation characteristics have been examined in the constant volume vessel (respectively electrically and optically). With an increase in charging time and also with increased electrode gap distance, spark ignition energy is respectively increased. Both features promote discharge kernel development and flame propagation. The significance of electrode gap distance for engine operation has been confirmed [13]. The combustion course in the mentioned study was visualized using the transparent engine, PLIF optical method and indicating research for 3 characteristic fuel-air equivalence ratios– φ=0.8…1.2. Increase in the electrodes gap distance from 1.0 mm to 1.4 caused an increase in the ignition energy in real engine conditions, which resulted then in reduction of ignition delay time. Further then, bigger flame speed has been indicated for all investigated φ as well as bigger heat release rate calculated from the dependency based on the pressure traces. Bigger value of the recorded pressure and consequently higher cylinder temperature when gap distance increased are considered as a source of increased NOx emission, but on the other hand, reduced HC emission. A positive correlation between ignitability of lean mixtures and the electrode gap distance has been confirmed– the greater mixtures volume is interacting with spark kernel the better ignition capability indicated.

The analysis of internal pre-chamber conditions has been performed and published in [2]. The conditions in the spark plug gap area are influenced by the jet of gas fuel injected into the top part of the ignition chamber. The injection in the static conditions generates different character of the charge movement in the top part of the ignition chamber. The injection process to the static ambient indicates jet development downstream the flow. However, the ignition chamber is being fed with charge transferred from the main chamber in the compression stroke, when the pre-chamber injection is being performed. In the investigated dynamic conditions air supplied from the auxiliary causes change in the jets trajectory and its division implied with constructional features of the ignition chamber– into the bottom of the chamber and into the spark gap area, which is important regarding the issues discussed in this study. This part of the gas jet executes the rotational movement in the top part of the ignition chamber and therefore impacts perpendicularly the discharge generated on the spark plug, which is assembled parallel to the pre-chamber vertical axis. Such conditions have been introduced to this research.

The application of bigger ignition energy impacts positively combustion stability and shifts the engine ultra-lean limit [15]. In the mentioned study, the discharge energy has been increased from 50 mJ to 250 mJ. At smaller ignition energy, the combustion stability (assessed using CoV(IMEP)) was deteriorated at λ=1.51. Application of 250 mJ discharge resulted in stable operation up to λ=1.81. It can be stated, that the ignition capability and ignitability of ultra-lean charges can be improved using a multi-discharge system or multi-coil ignition system leading to increased ignition energy [15, 16]. However, the energy released from the spark-jet ignition is significantly greater [17].

Studies discovered the possibility to estimate plasma vibrational temperature discharge using optical signal recorded with a high-speed camera and thus indicate energy transfer to the mixture of air with fuel also in gaseous state of matter [18, 19].

2. Methodology

The main objective of the study was to analyze the impact of charge movement characteristic for the prechambers top part (spark plug location) on the spark plug discharge. The investigated object was a spark plug with a single mass electrode set on the gap of 0.8 mm. Measurements were performed on the optical test stand (Fig. 3). The spark generated between spark plug electrodes was being recorded with high-speed camera LaVision HSS 5. The recording area has been adequately expanded to the camera matrix with a lens system. The investigations have been performed in the ambient pressure and the temperature, however, to simulate the charge motion occurring in the interior of the ignition chamber the compressed air was directed from the air nozzle to the spark gap area. The span charge velocity has been measured using thermo-anemometer. The spark plug has been supplied with energy from ignition system from Mechatronika Kedzia, adjustable regarding the loading parameters in the primary circuit of the ignition coil, impacting, therefore, released energy. The discharge energy has been calculated based on the values of voltage (probe HVP40) and current in the secondary coil circuit.

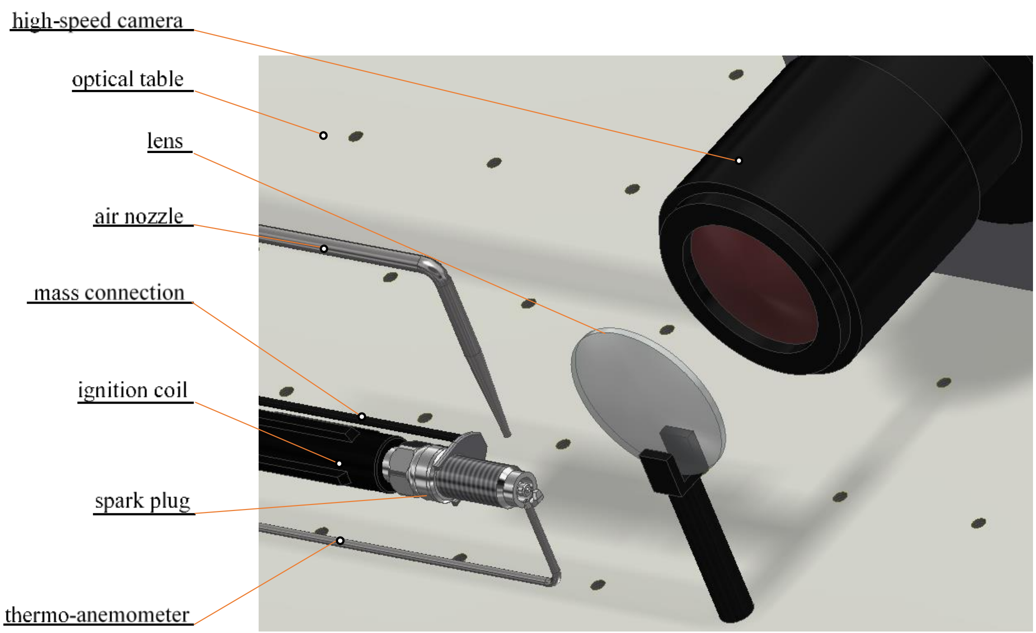

Fig. 3. Test setup to the investigations on spark plug discharge

The investigations were divided into two main campaigns with respect to the subsequent discharge phases– arcing and glowing. Both phases generate an optical luminescent signal, which was recorded. Mentioned processes differ in the duration time, so the recording parameters were adequately adjusted:

- Arcing phase: 140 kHz, resolution 127x47 px;
- Glowing phase: 30 kHz, resolution 384x256 px.

The images have been post-processed using LaVision Davis and FiJi ImageJ software. Recorded images represent two-dimensionally the analyzed phenomena. Pictures captured in the arcing phase are extruded into the third dimension to show clearly the intensity distribution.

3. Spark plug discharge intensity

Spark plug discharge indicates early unluminescent phases and subsequently the phases generating luminescent optical signal [compare with Fig. 2]. The analysis of discharge event in the entire time of its occurrence requires optical studies complemented with detailed investigations on the electrical signal in a high-voltage circuit but is not an objective of this study, which focuses on the properties of the dual stage combustion system and therefore on the interaction between spark with charge in the ignition chamber. First investigated phase was the arcing phase indicating an intensive luminescent optical signal. The dynamic conditions in the spark plug gap area have been compared to the sparking in the static conditions. The air was delivered to the spark gap perpendicularly to the X-axis, in the Y-direction (Fig. 4).

a) b) c)

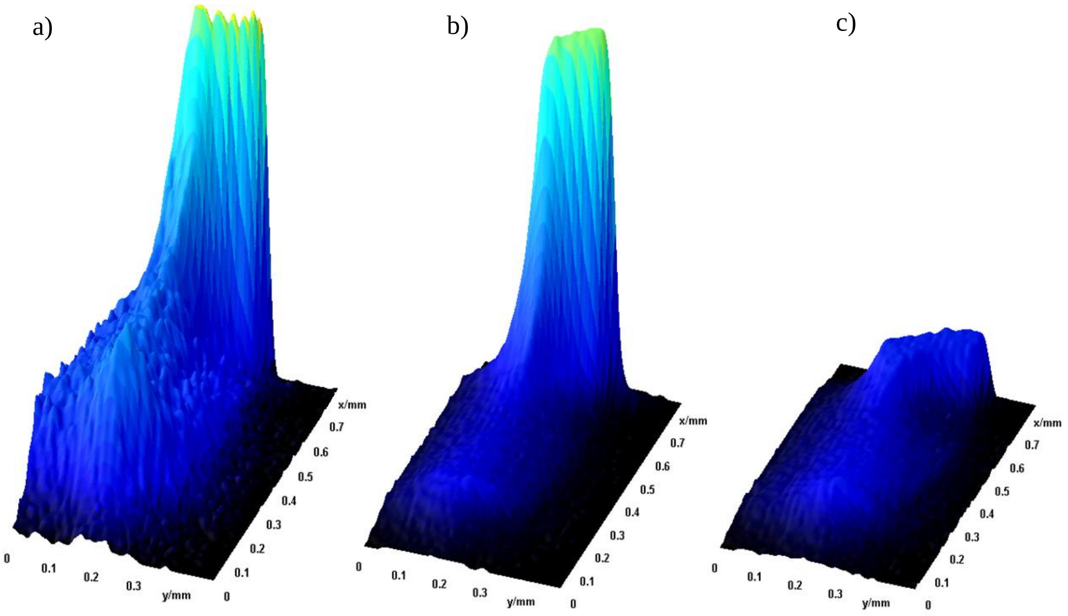

Fig. 4. Spark plug discharge in the arcing phase; a) static conditions, b) v=3 m/s, c) v=6 m/s

During the visualized sparking process (Fig. 4), the energy of 14 mJ has been released. Images represent the discharge 7.14 µs after introducing the recording process started parallel with the ignition trigger. One can notice, that bigger luminescence intensity has been registered in the area close to the central electrode, which takes place in the static as well as in dynamic conditions, indicating a tendency to decrease with an increase in air velocity. Also with the increase of air velocity, the most luminescent region is being shifted downstream the flow. This shift has the source in the movement of ionized charge caused by the flowing medium. The possibility to compensate the mentioned reduction in discharge intensity with increase in coil loading parameters to store and release bigger energy. Longer coil loading has been applied and the discharge energy has been increased to 34 mJ. The area and mean discharge intensity have been calculated from recorded images and compared (Fig. 5).

a) b)

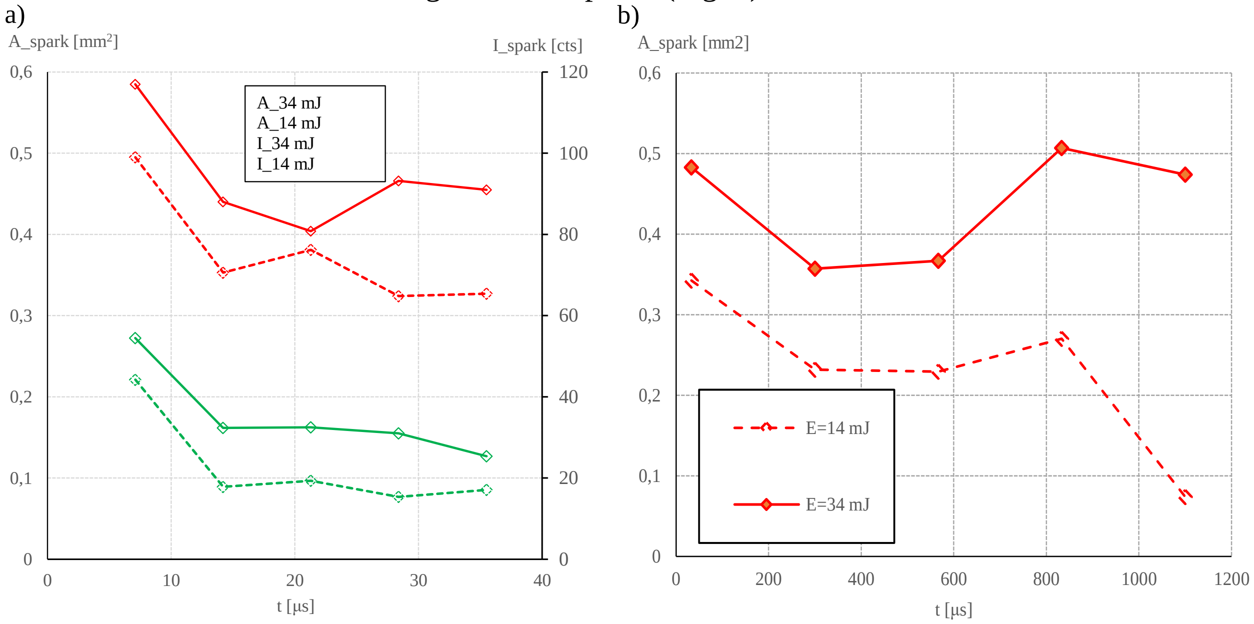

Fig. 5. The area and luminescence intensity of 14 and 34 mJ discharge

According to Figure 5, investigations have been performed in the static conditions. Discharge area represents an area of its flat captured exposition. This magnitude delivers valuable information to compare sparking events and assess the heat transfer area, which is very important for the fuel-air mixture inflammation in the engine. Further comparison is being performed based on the luminescence intensity. The discharge energy has been increased by 143%. First values marked on the diagrams (Fig. 5a) characterize the arcing phase. In the analyzed time period, the area of discharge indicates in average the 18 % increase. Further stages also indicate a bigger area. Up to 566 us, the 34 mJ discharge has in average 24 % bigger area, than 14 mJ discharge. From this time, the area of 14 mJ discharge decreases intensively. Based on this, it can be stated, that arcing phase is more intensive in terms of heat release that the big part of the energy has been transferred as heat and on the processes preceding transferring the energy from the spark kernel to the mixture. In the further discharge stages (Fig. 5b) the tendency is being held, but the rapid decrease of discharge area has been observed after approximately 1 ms from the start of ignition for 14 mJ discharge. After this time period spark is being quenched, while 34 mJ discharge is still registered. As already mentioned, sparking energy is combined with its time and depends on charging parameters. Further measurements were conducted in the dynamic conditions and with 34 mJ discharge energy (Fig. 6).

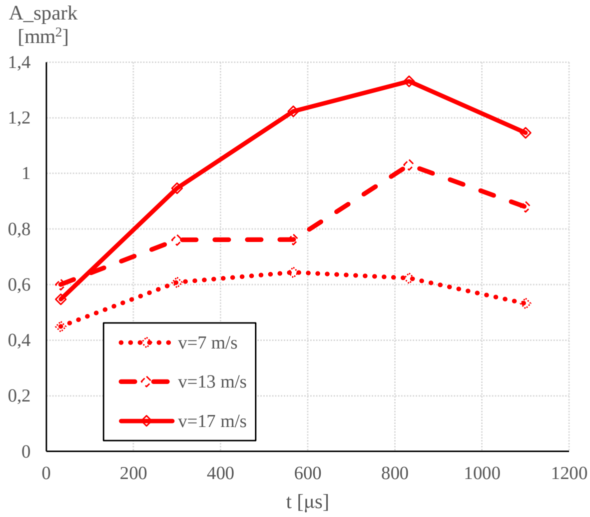

Fig. 6 Spark plug discharge area in the dynamic conditions for span air velocity 7 m/s (dotted line), 13 m/s (dashed line) and 17 m/s (solid line)

In contrast to the static conditions, spark kernel area in the dynamic conditions increases after discharge initiation (Fig. 6.). This increase is a consequence of spark elongation, which takes place due to the shift of ionized charge. The characteristic tendency is being noted– the increase in charge velocity results in bigger elongation of the spark kernel. Based on the assumption of sufficient ignition energy to generate discharge it can be stated, that charge motion in the gap volume promotes spark elongation and increases the heat exchange with its ambient.

4. The rotational position of the spark plug

As confirmed, spark kernel is influenced and deformed by the charge motion inside the prechamber, which is affected by constructional features of the chamber's interior. Another aspect of the investigated spark-jet ignition system is the spark plug angular position (Fig. 7).

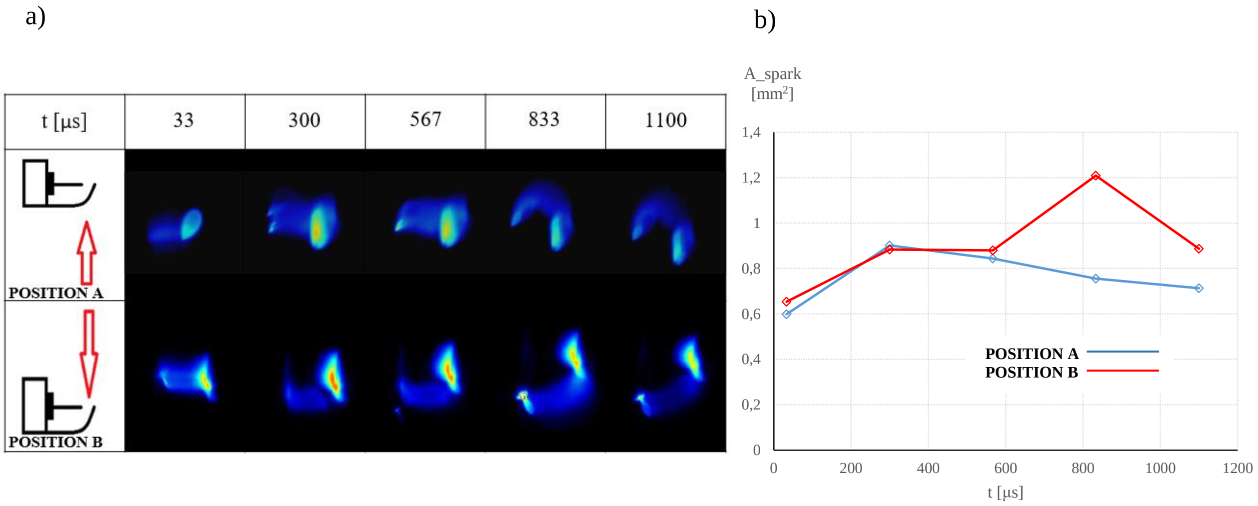

Fig. 7. Spark plug discharge in terms of variation in rotational position; a– optical data, b–calculated (image-based) discharge area

Two different positions have been examined. In the position A (Fig. 7a) the electrode gap was particularly covered with side electrode, which in variant B was oppositely positioned to the flow direction. The same flow velocity (v=7 m/s) has been applied in both cases. Based on the optical signal, in both cases, spark kernel is being elongated. However, the spark kernel in position B is being moved to the free volume and the luminescence intensity drops. The kernel indicates the tendency to break. Position B causes shifting the spark kernel to the volume between the electrodes. This promotes beneficial conditions to the ionization in the volume close to the spark and finds its confirmation in the optical data (Fig. 7a). Bigger spark luminescence is combined with significantly bigger kernel area in the late stage of discharge (Fig. 7b).

5. Summary and conclusions

The ignition issue in the two-stage combustion system has been experimentally investigated with optical research methods. The experiments led to the parametrization and explanation the ignition imperfections caused by specific conditions occurring in the analyzed 2-stage combustion system. These conditions have been measured in terms of change in charge motion characteristics– the velocity of charge moving in the electrode gap volume and also its direction. Performed investigations allow to formulate conclusions:

- Charge motion impacts spark plug discharge course at all the stages,
- In the arcing phase, increase in charge velocity to 6 m/s causes shifting the ionized charge within the electrode gap volume resulting in shifting the discharge downstream the flow and significant reduction of the kernel luminescence intensity due to the transfer of ions outside the kernel volume,
- the increase in spark plug discharge energy from 14 mJ to 34 mJ (caused by an increase in coil charging time) results in increased spark luminescence intensity and its volume, what provides significantly intensified heat transfer to the discharge ambient, potentially the ignition capability,
  in the single-mass electrode spark plug, the position B (with the free flow) to the gap volume provides more intensive (in terms of its luminescence and volume) discharge than the position A.

Acknowledgments

The research presented in this paper was performed within the European Research Project Horizon 2020, grant agreement No. 652816, Gas-Only Internal Combustion Engines. This research task was directed by Prof. K. Wislocki, the leader of the Research Group. The authors wish to thank the EU for funding the work and express their acknowledgments to all persons, who have had their contribution in this study and the laboratory works.

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