Initiation Ignition of the Spark Plug

Aleš Dittrich and Stanislav Beroun
Technical university of Liberec, Liberec, Czech Republic
Email: ales.dittrich@tul.cz, stanislav.beroun@tul.cz

Abstract—**This paper deals with the initiation mixture ignition by spark plug ignition combustion engines. Attention is paid to the description of the initial conditions in the engine of the spark-ignition engine at the moment before the spark overflow between the spark plug electrodes. A substantial part of the contribution is then devoted to experimental research and measurements on a vehicle petrol engine using the available (and described) techniques available to the TUL laboratories.**

Index Terms—**spark plug, visualisation, ignition, SI engine, integrated chamber, visioscope.**

I. Introduction

The combustion of a fuel-air mixture in a combustion engine cylinder is a complex physicochemical process that results in oxidative reactions in the fuel / air mixture (oxygen). In the cylinder of the combustion engine, this is done under conditions of rapidly changing temperatures and pressures of the fuel mixture. It has a different course for gasoline engines and another for diesel engines. It depends on the specific properties of the fuel used, on the way the fuel mixture is formed and on its quality (homogeneity, richness) and, above all, on the method of initiation of combustion.

A. Ignition of the Fuel Mixture

The initiation of combustion of the fuel mixture in the spark-ignition engines is carried out by means of a high-temperature ignition mechanism by means of high-voltage power supply to a very small volume of the prepared fuel-air mixture. High-voltage discharge on the spark plug electrodes will increase the temperature of the very small volume of the fuel mixture. This initiates a pre-oxidation reaction in a fuel mixture which produces the necessary activated particles (radicals, peroxides, ions - endothermic pre-oxidation reactions) and which culminates in an outbreak (exothermic reaction) and the subsequent development and spread of the flame other fuel mixtures.

With high-voltage electric discharge, an extremely high temperature rise occurs (the temperature between the electrodes locally exceeds 104 ℃). In addition to the thermal dissociation of molecules, intensive ionization of the environment around the spark gap occurs. This causes an immediate reaction of the components in the fuel-air mixture at high velocity and ultimately results in the completion of this initial phase of the ignition by creating a viable ignition outburst. For a homogeneous fuel-air mixture with a composition close to the stoichiometric mixing ratio, the ignition energy in the size of 3-5 mJ is sufficient, applied over 0, 6-1 ms. The spark-ignition mechanism of the high-voltage discharge mixture has several phases: this graphically shows the distribution of the temperature field near the spark gap of the spark plug in Fig. 1. [1]-[3].

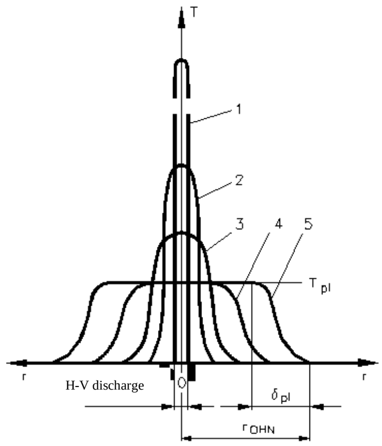


Figure 1. Scheme of formation and individual phases of ignition outbreak development. [3].

•1. At the time of a high-voltage discharge, the temperature between the spark plug electrodes grow rapidly (curve 1).

•2. By conducting the heat from the point of discharge the zone of elevated temperature (curves 2, 3) begins to expand, the temperature at the point of high voltage discharge decreases.

•3. Once the oxidation burst of the mixture begins, the temperature drops slow down, heat dissipation in the environment is compensated for by the released heat during oxidation and burning from the focal point of the discharge into another volume. Vojnov [3] states that for the reliable development of fire from the spherical bulkhead, the radius of ignition focal length (r_{OHN}) is 3x greater than the flame zone width at the head of the burning mixture, ie $r_{KRIT}=3\delta_{pl}$. The high-voltage discharge period should last at least until the ignition has been reached. The spherical surface of the flame with the $r_{OHN} \geq r_{KRIT}$ dimension is then able to separate the further development of the combustion process.

Great importance for initiating the combustion process (ie combustion of the fuel-air mixture with heat release) are pre-flame reactions (processes of initiation of the combustion process) that take place in the focal point of

Manuscript received August 1, 2018; revised June 15, 2019.

doi: 10.18178/ijmerr.8.6.954-959

the burning and in which so-called activated particles are formed. Flame formation is associated with an oxidative reaction with a relatively small increase in temperature, characterized by a weak bluish (cold flames whose "fluorescence" is only distinguishable on a dark background - the chemiluminescence of the luminescence is caused by the formation of HCHO formaldehyde).

By cold-flame and other pre-oxidation reactions in the focussing flame formation, the activated particle concentration increases until an open flame occurs. An important feature of a flammable fuel (in this case a motor fuel) that affects the processes involved in the initiation of combustion is the ability to provide sufficient dynamics of pre-flame (pre-oxidation) reactions under certain conditions. The ignition temperature of the fuel mixture is not a physical quantity for a given fuel - it depends on the size and construction of the fuel molecule, but it also affects other conditions (mixing ratio, total heat balance in the ignition or ignition point, etc.) and time disposition for the dynamics the ignition process. The interrelation of these parameters describes the Semenov relation (1).

$$\tau \cdot p^n \cdot e^{\frac{-E_A}{R \cdot T_s}} = konst. \tag{1}$$

where

- τ - ignition delay, so called induction time [s],
- T_s - temperature of the fuel mixture [K],
- p - pressure of the fuel mixture [bar],
- n - order of reaction (usually $1 < n < 2$),
- E_A - activation energy [kJ kmol^{-1}],
- R - universal gas constant [kJ K^{-1} kmol^{-1}].

Under comparable conditions, the ignition temperature is determined primarily by the amount of activation energy. E_A as the activation energy is in some sense a fuel parameter (fuel mixture) that expresses the requirement for a certain level of internal fuel energy (fuel-air mixtures) needed to trigger oxidation reactions. The explanation of the ignition mechanism of the fuel mixture is based on the condition that first the energy level of the fuel mixture molecules (R T) exceeds the value of the activation energy in a certain volume of the fuel mixture so that the required initial concentration of the activated particles (active radicals) required to generate an open flame, followed by spontaneous sequencing of chain combustion reactions in the already burning fuel-air mixture. For hydrocarbon fuels, the magnitude of activation energies is in the range of 20-400 MJ / kmol: for example, for diesel, activation energy is reported in sizes up to 45 MJ / kmol, petrol fuels have an activation energy of 90-150 MJ / kmol, gaseous hydrocarbon fuels then in the range of 250-400 MJ / kmol. When increasing the temperature of the fuel mixture, the activation energy decreases (for petrol fuels up to 40 MJ / kmol) [3]: increased internal energy (ie higher kinetic energy of thermal movement of molecules) contributes to overcoming the energy potential needed to start the reaction.

II. Indirect Ignition

Indirect ignition of a fuel mixture in a spark ignition engine is also referred to in the literature as an indirect ignition and in English, for example, as a flame-jet [4], jet-ignition [5], [6] or chamber / prechamber ignition [7]-[9]. In all the above mentioned cases, the main objective of such a solution is to cause the combustion of a relatively small volume of combustible mixture (in units of % compared to the cylinder volume) and to ignite the fuel-air mixture remaining with this combustible fuel mixture (turbulently flowing outside the chamber). The difference between individual solutions is in the way of fuel supply, respectively. fuel mixture to the spark plug. In these cases, the chamber spark can be divided into:

- "Active" with fuel in the chamber,
- "Passive" with the fuel supply outside the chamber and the fuel-air mixture into the chamber by moving the piston from the bottom dead center to the upper dead center.

The Department of Vehicles and Engines (KVM) of the Technical University of Liberec (TUL) has long been addressing the issue of combustion of combustion in the piston combustion engines by the so-called chamber ignition (or the research of spark plug with integrated chamber - SPWIC). Blažek has also dealt with this topic in his dissertation work [10].

The KVM internal documents state that the experimental research program (on KVM TUL) to verify the effect of the protected space around the spark plug electrodes in the chamber, where the conditions for the development of the ignition outbreak and combustion of the fuel mixture in the chamber and the exhaust of the combustion gases and of the combustible air out of the spark plug chamber into the combustion chambers in the engine cylinder accelerate the combustion of the fuel mixture in the engine cylinder, it was in the first stage (which was carried out in 2002-2006) carried out on only one cylinder of gasoline and gas engines. The result confirmed that the fuel-air mixture in the engine cylinder is a significant potential with real possibilities to further improve the parameters of today's petrol engines.

An indicator of the quality and stability of the combustion process in the cylinder of the internal combustion engine is the variability of engine operating cycles. Variability (referred to differently - for example VAR, CoV, ...) of cycles is usually expressed as the ratio of the standard deviation to the average value of the given parameter. Generally, the relationship for calculating parameter variability (xy) can be written according to (1). The evaluation and determination of combustion parameters from the measured indicator diagrams was carried out using SW Concerto.

$$VAR_{xy} = \sigma_{xy} \,.\, x_y^{-1} \tag{2}$$

- x_y parameter value determined by thermodynamic analysis and statistical processing of a larger set of indicator diagrams in the engine operating mode under investigation (in the case of a high-pressure engine indication, a data set of 100 or 150 consecutive engine operating cycles is typically recorded).

- σ_{xy} the standard deviation of the given parameter from the statistical processing of the set of indicator diagrams.

For a modern gasoline engine in higher engine load modes, the variability of the mean pressure indicated is $VAR_{pi} \approx$ 1-2%. With the engine load decreasing, p_i variability increases, with high variability in particular idling mode. In addition to the inter-cycle variability of the mean indicated pressure, the variability of the maximum (so-called combustion) pressure in the cylinder is also interesting. Beroun [1-2] states that VAR_{pmax} values for spark ignition engines are ≈ 8-9% (at $\lambda = 1$ and $VAR_{pi} \approx 2\%$) during the normal burning process, ie. without knocking.

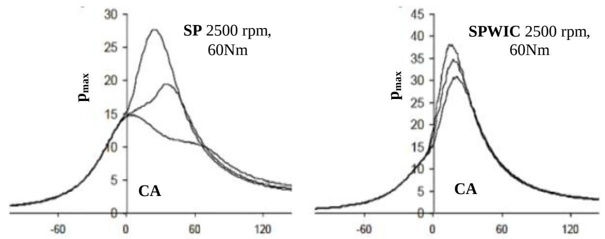


Figure 2. Comparison of gasoline engine cylinder pressure (VZ1 = 0.35 dm3, homogeneous combustion air mixture λ = 1, electronic control) at standard ignition and ignition using a "folded" ignition chamber (1.65 cm3 chamber volume, fuel injection cylindrical compartments). Pressures from working cycles with the highest, mean and lowest pmax values from a set of 150 consecutive engine operating cycles. Source: internal KVM documents.

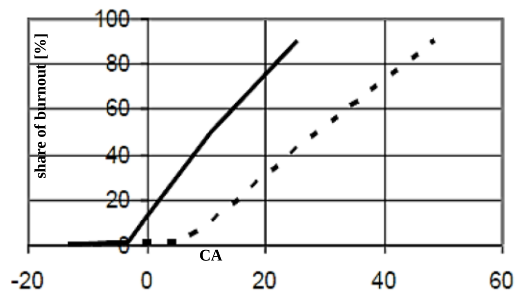


Figure 3. Running of the fuel-air mixture in the engine cylinder at spark ignition with a classic spark plug (dashed line) and chamber ignition (solid line). The parameters of the burning parameters are determined from the thermodynamic analysis of the measured pressure and statistical processing of the burning parameters from the same measurement set as the pressure steps in Figure 1. Source: KVM internal documents.

III. EXPERIMENT

A. Visualization Technique

The AVL VisioScope (with accessory) allows to view and visually track events in the combustion chamber or in the intake and exhaust ducts of both petrol and diesel engines. AVL's Visioscope Visualization System works with electronic image capture, transmission and processing so that the user-selected frequency gradually records the image in the engine cylinder in the individual crankshaft positions (for this reason, the system is connected to the indicating device from which it receives position information crankshaft). The resulting course of the observed event is therefore composed of images recorded for the selected area from different engine operating cycles. The latest version of AVL Visioscope 1.5 was used to record and evaluate the video record.

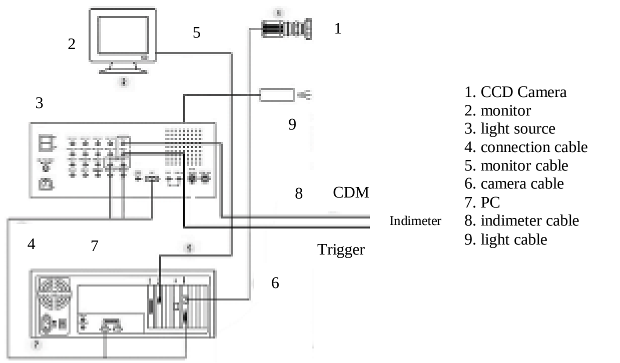


Figure 4. Wiring diagram for visualization devices - Visioscope.

For visualization of burning in a spark-ignition engine, the AVL Visioscope uses a high-sensitivity Di-CamPro camera that works only in black and white and the recorded image is converted to a color format using the special SW AVL (changing the image from black and white to color is done by setting the temperature distribution scale in SW AVL, but it is also affected by the temperature in the engine cylinder which determines the basic color of the image, which is reflected in the color differences of the images for different engine loads.) Which clearly shows the temperature changes in the high-voltage discharge and combustion of the fuel-air mixture.

Due to the procedure of recording the image in the individual crankshaft positions and subsequent storage of the data, the individual pictures are taken at a relatively low frequency and each subsequent picture is therefore always from another engine duty cycle. In order to suppress the successive variability of successive cycles (inter-cycle variability), selecting the visualization settings can be used to capture multiple images for the same crankshaft position, and a "average" image for each crankshaft position is created by statistical processing of the recorded data. From such records, a burn-out visualization is created, from which separate images can be selected for each crankshaft position.

1) *Endoscopes*

The visualization technique mentioned uses two basic types of endoscopes (according to the current application). Basic distributions can be made as follows:

• Cooled endoscope

Endoscope designed to monitor the processes in the engine cylinder and the engine running. The endoscope has integrated cooling air inlet chambers (must meet manufacturer's specified purity and humidity parameters) that is connected directly to the endoscope. The endoscope is then inserted into a capsule that ends with a quartz glass ampoule and protrudes into the engine's combustion chamber (its main function is the optics protection located at the end of the endoscope). The cooled endoscope is of a relatively small diameter (4mm).

• Endoscope with illumination

An endoscope with illumination is designed to monitor events in areas with low thermal stress (up to 150 ℃). In the body of the non-cooled endoscope, a light guide for intensive white light from the Visioscope control unit is incorporated into hard-to-reach areas that are necessary to record ongoing events. Because of the integrated light guide in the body of the endoscope, this body is larger than the endoscope cooled (8mm).

Both endoscope variants have an end portion with a lens optic adapted for either direct observation (i.e., a 0 ° vertical axis of deflection angle) or side viewing with angles of deflection from the vertical axis of the endoscope either 30 ° or 70 ° (or 60 °) . The field of view of the optic is bounded by a cone at a top angle of 67 ° (fictiously emerging from the end portion of the endoscope).

If necessary, use of recording visualization techniques requires the engine to make adjustments to enable the required components to be installed exactly according to the manufacturer's instructions. Due to the relatively small dimensions of today's combustion engines and the relatively rich accessory of today's engines, it is quite difficult to find a suitable access path for the visualization technique to produce the desired recording.

2) Preparation before the experiment

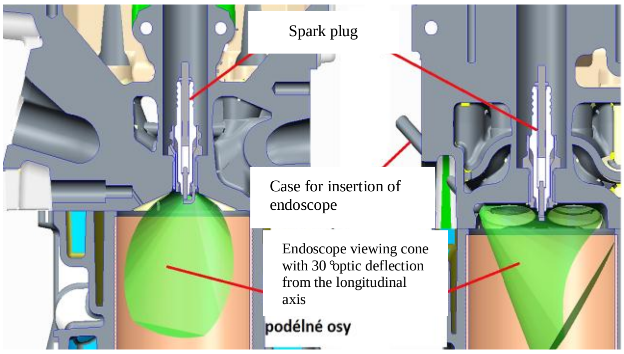


Figure 5. Drawings of cylinder head modification with an embedded endoscope (with a 30 °deflection of the optical axis) with a view of the viewing cone with respect to recording the processes in the spark plug area. The drawing in the left part of the figure shows the situation in the cross section of the cylinder, in the right part of the figure shows the situation in the cylinder in the longitudinal axis of the motor.

Necessary preparation before the experiment itself is to verify the correct location of the endoscope in the cylinder head on the observed object using the CAD system (Creo Parametric) and model 3D data. A simplified view of the optical access to the engine cylinder where the object being viewed is a spark plug is shown in Fig. 5 and 6. The drawings in Figure 5 illustrate the situation when using an endoscope with a 30 ° optical axis offset from the vertical axis of the endoscope, endoscope with a 60 ° divergence from the vertical axis of the endoscope. The optic angle of both endoscopes is the same - 67 °.

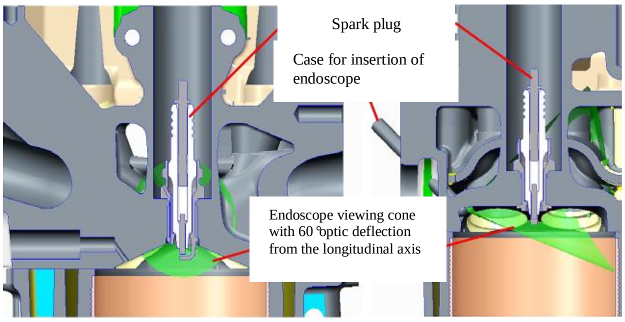


Figure 6. Drawings of cylinder head modification with an embedded endoscope (with a 60 °optical axis offset), with a view of the viewing cone with respect to recording the processes in the spark plug area. The drawing in the left part of the figure shows the situation in the cross section of the cylinder, in the right part of the figure shows the situation in the cylinder in the longitudinal axis of the motor.

The actual view of the engine cylinder by means of a cooled spark plug endoscope is shown in Figure 7. The images were taken with illumination (using intense white light provided by the visualization technique) of the cylinder space. The light source was placed in the spark plug compartment for recording images (taken when the engine was turned off). The glare of the images below is caused by the use of an intense light source.

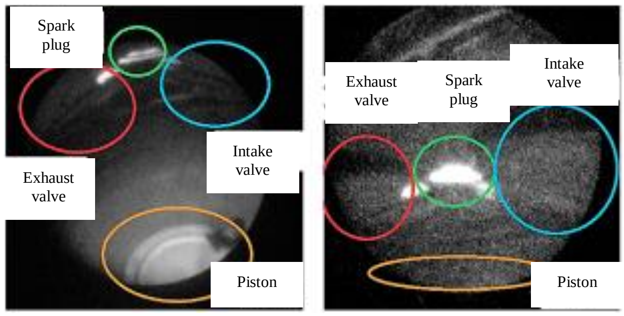


Figure 7. The 30 °deflection endoscope optic on the left shows a view of the spark plug (top), a small portion of the compression space in the cylinder head, and the cylinder space under the spark plug. The image on the right is for a 60 °optic diverter endoscope: a view of the spark plug (in the center of the image), a larger portion of the compression space in the cylinder head in the spark plug region, and a smaller portion of the cylinder space under the spark plug.

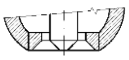
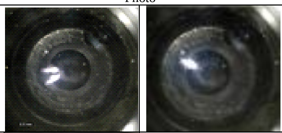
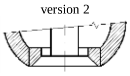
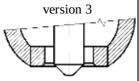
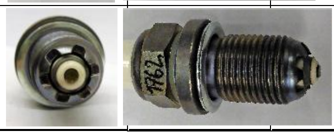
B. *Experimental Engine and Spark Plugs*

Experimental works on the tested variants of spark plug with integrated chamber were made on testing engine in laboratory belongs to Laboratory of power units. Each variant (shown in Table II.) was prepared as assembly of "prefabricated" spark plugs which basic parts (case and insulator with center electrode) in cooperation with company Brisk Tábor. For measurement was prepared engine EA111.03E (high pressure indication for each cylinder, pressure sensors GU21D and measurement device AVL 619 Indimeter) – parameters are in the Table I.

TABLE I. ENGINE PARAMETERS

Type	SI, 12 valves, DOHC
Bore X Stroke	76,5 X 86,9 mm
Number of cylinders	3
Swept volume of engine	1198 cm^3
Maximum power	51 kW
Maximum torque	112 Nm
Compression ratio	$10{,}5 \pm 0{,}3$:1
Cooling	water

TABLE II. TESTED SPARK PLUGS

Version	Photo	Description
version 1 		The discharge takes place mostly inside the chamber.
version 2 		The discharge takes outside and inside the chamber.
version 3 		The discharge takes outside and inside the chamber.
classic 1		
classic 2		

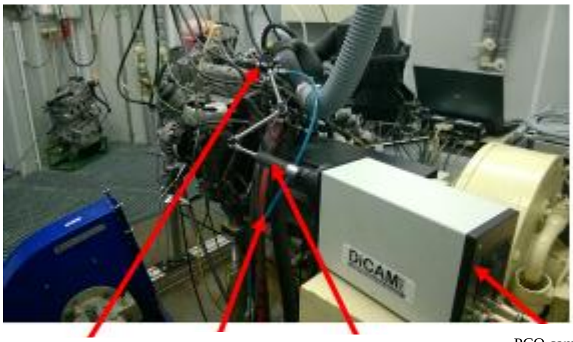


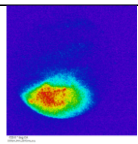
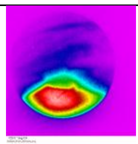
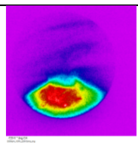
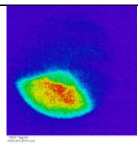
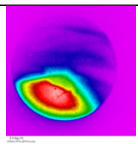
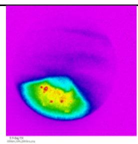
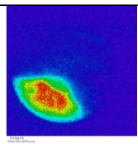
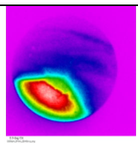
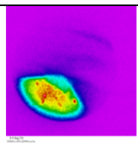
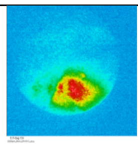
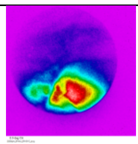
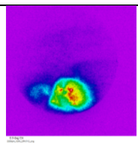
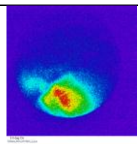
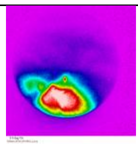
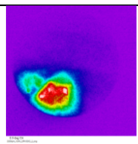
Figure 8. Laboratory setup.

Figure 8 shows laboratory setup with DiCAM pro camera and cooled endoscope.

IV. RESULTS AND DISCUSSION

To compare the spark plugs, visualization of burning from ignition to advanced flame development was performed. Visualization was performed in medium engine speeds at very low (6Nm), medium (67Nm) and full load. After evaluating the suitability of viewing the observed events in a cylindrical endoscope with an offset of the optics of both 30 ° and 60 °, a variant of the 60 ° divergence endoscope was selected to display the results. The captured images show the situation in the cylinder from the ignition to the top dead center with a 2 degree crankshaft position (ie, with a time step $\Delta\tau$ = 0,11 ms). Images are the result of the statistical processing of 10 recorded "pictures" in the cylinder in each individual crankshaft position. The following table (Table III.) shows only the flame development scenes in the upper dead center, ie practically at the beginning of the main burning phase.

TABLE III. VISUALISATION RESULTS

version	6Nm	67Nm	100%
version 1			
version 2			
version 3			
classic 1			
classic 2			

V. CONCLUSION

The results of the experiments with spark plugs with integrated chamber show the positive influence of the sparking method of the prepared homogeneous mixture on the development of the initial phase of combustion and confirm that the ignition of the mixture by means of a spark plug with an integrated chamber has a beneficial effect. This is evidenced by the reduction of ignition leakage and faster burning in the initial phase of combustion, as evidenced by the visualization images mentioned above (in the case of a spark plug with an integrated chamber, a combustible mixture burns in the area of the upper dead center in the entire volume above the piston, not only locally, in the case of a classic spark plug).

ACKNOWLEDGMENT

The results of this project LO1201 were obtained through the financial support of the Ministry of Education, Youth and Sports in the framework of the targeted support of the “National Programme for Sustainability I” and the OPR&DI project Centre for Nanomaterials, Advanced Technologies and Innovation CZ.1.05/2.1.00/01.0005.

REFERENCES

[1] S. Beroun, *Thermodynamics Working Cycle of Internal Combustion Engine, Combustion Process in Piston Internal Combustion Engine*, Technical University in Liberec, 2009.

[2] S. Beroun, *Basics of Burning Theory, Combustion Process Mechanism in Piston Combustion Engines*, Technical University in Liberec, 1998.

[3] A. N. Vojnov, *Processy Sgoranija v Bystrochodnych Poršněvych Dvigatěljach*, Mašinostrojenije, Moskva, 1965

[4] B. H. John, *Internal Combustion Engine Fundamentals*, New York: McGraw-Hill, 1988.

[5] P. A. William, T. Elisa, H. Andrew, C. Xuefei, and G. Zhu, *Spark Ignition and Pre-Chamber Turbulent Jet Ignition Combustion Visualization.*

[6] A. William. (2011). Turbulent jet ignition pre-chamber combustion system for spark ignition engines. *Inventor: William Attard.* [Online]. Available: http://www.google.com/patents/US20120103302

[7] *Engine Technology International.* 2017.

[8] D. C. R. Fábio, R. M. Braga, and R. D. O. A. Coelho, “Roberto berlini rodrigues DA COSTA a Ramón Molina VALLE,” *Numerical Analysis of the Fluid Flow in A Prechamber for A Spark-Ignition Engine*.

[9] M. GmbH. (2012). Spark plug. *Inventors: Olaf Berger, Friedrich Schäfer.* [Online]. Available: http://www.freepatentsonline.com/EP2690726.pdf

[10] J. Blažek. *Research and Development Of Cell Ignition For Vehicle Engine.* Liberec, 2008. Dissertation. Technical university in Liberec. Thesis supervisor doc. Ing. Lubomír Moc,

Aleš Dittrich was born in November 1985 in Turnov – Czechoslovakia. He graduated at Gymnasium in Mnichovo Hradiště, Czech Republic, on May 2005. After that he started to study Mechanical engineering at the Technical university of Liberec, Czech Republic. He finished his studies in 2010 as a engineer with the field of internal combustion engines and after that he started to study Ph.D at the same university and finished his Ph.D. in 2018 with the field of internal combustion engines. From 2011 to 2013 he finished pedagogical studies and become Ing.PAED.IGIP.

Aleš used to work in several companies during his studies as a mechanic for Škoda company. After he finished his master thesis. He started to work in Technical university of Liberec as a Junior researcher. He used to work on several public and also private project as a member of the team and also as a teamleader. He was also a member of the project for education the youth people, where he worked as a lecturer. During 2011 to 2017 he was employed in Škoda R&D center in Mladá Boleslav, Czech republic. From 2017 to 2018 he worked in specific project in The Institute of Information Theory and Automation (UTIA) - a public non-university research institution which administratively falls under the Czech Academy of Sciences From 2018 he worked as an professor assistant at the Department of vehicles and engines at the Technical university of Liberec, Czech republic. His field of research are internal combustion engines. Between 2010 and 2018 he published as an author or coauthor about 50 manuscripts.

Stanislav Beroun was born in Desember 1938 in Horní Újezd – Czechoslovakia. He finished his studies in Technical University of Liberec in 1961 as an engineer. He become a professor in 1998 with the field of internal combustion engines.

Stanislav worked in LIAZ company as an test engineer with the field of internal combustion engines between 1962 and 1970. He started to work in Technical university of Liberec in 1970 as a researcher and teacher. He used to work on several public and also private project as a member of the team and also as a teamleader. His field of research are internal combustion engines. He published as an author or coauthor many manuscripts and studentbooks.