Investigations on gas-air mixture formation in the ignition chamber of two-stage combustion chamber using high-speed Schlieren imaging

Wojciech Bueschke^{1,*}, Maciej Skowron¹, and Krzysztof Wislocki¹

¹Poznan University of Technology, Faculty of Machines and Transport, ul. Piotrowo 3, 60-965 Poznan, Poland

Abstract. Combustion of the lean mixtures in the spark ignition engines provides higher thermal efficiency compared to the combustion of the stoichiometric mixture but is more restrictive to the ignition systems. Due to the limitations of conventional ignition systems, advanced concepts are being used, e. g. spark-jet ignition. Presented research has been carried to determine: 1. The impact of fuel injection pressure on the velocity of mixture formation, 2. Fuel distribution inside ignition chamber in defined phases of chamber filling, 3. Influence of chamber back-pressure on gas jet development. Investigations have been carried using the ignition chamber providing optical access. The visualization has been done with Schlieren-method with "Z"-setup basing on two $\phi = 150$ mm parabolic mirrors. Images have been recorded with LaVision HSS5 camera with CMOS transducer. The paper contains a comparison of gas penetration parameters for a different injection pressures and chamber backpressures. The injection into the quasi-static air has been compared to the injection in dynamic conditions. It is stated, that both injection pressure and chamber back-pressure influence gas jet-development in the ignition chamber. The regions of the chamber with increased swirling and therefore providing more efficient micromixing have been identified.

1 Introduction

Big worldwide demand for the fuel energy in combination with limitations in available crude oil resources is a significant fact by the intensification of research into alternative fuels. Between the alternative fuels, important advantages present the group in the gaseous state of matter, for example, relative high calorific value and octane number. It determines the rise of their exploitation as well as motivation to conduct the study on the ignition system for CNG combustion systems [1-3].

Combustions systems can be divided, in terms of air-fuel stoichiometry, into the rich-burn and lean burn. The lean burn combustion process (with high air excess ratio) shows in general higher thermal efficiency than combustion of rich mixtures [4, 5]. However, the concentration of fuel in the mixture impacts the energy demand to initiate the combustion process, as is it presented in Fig. 1.

According to the Fig. 1, the reduction of methane concentration under 8% causes a rapidly rising demand for the energy to ignite the mixture. The maximal portion of the energy transferred to conventional spark ignition system, consist a limitation in the igniting of very lean mixtures, over the $\lambda = 1.7$ [6]. An enhanced ignitability in the combustion system can be obtained using advanced ignition systems, as a laser, corona ignition or turbulent jet ignition. The last mentioned system is

especially important due to the implementation of additional chamber resulting in different on-ignition mechanisms.

Fig. 1. Minimum ignition energy of the air mixture with methane [7].

The combustion system with spark-jet ignition is equipped with a pre-combustion chamber located in the cylinder head of an engine, presented in the Fig. 2.

As it is presented in Figure 2, ignition chamber (1) is assembled in the cylinder head (2) and located on the top of the main chamber (7). There is a spark plug (4) located in the enclosure. The fuel (5) is supplied to the ignition chamber volume (3), what will be described in next section. The combustion of pre-chamber charge is initiated with a conventional ignition source. The bottom

* Corresponding author: wojciech.bueschke@gmail.com

of ignition chamber consists the nozzles providing the mass transfer between the chambers. During the compression stroke, the charge from the main chamber is being transferred to the ignition chamber. Pre-combustion in this chamber results in pressure rise over the pressure in the main chamber and causes mass transfer into its volume. Hot jets penetrating the main chamber provide inflammation of the main charge.

Fig. 2. Combustion system with spark-jet ignition.

Combustion in the main chamber is preceded by several consecutive processes occurring in the ignition chamber, influenced by mixture formation in it. However, the combustion process can be particularly described by indicators calculated from the indicating data, the optical analysis of mixture formation is necessary [8-10]. The registration of methane jet development in the air ambient can't be executed using direct high-speed imaging due to its transparency. Shadowgraph methods are required. The shadowgraph methods are based on the change in refractive index, which is given by:

$$n = \frac{c}{v_l} \quad (1)$$

c – light velocity in the vacuum ambient,
 v – velocity of light in the analyzed medium.

The CNG-jet development in terms of variable injection pressure and chamber back-pressure has been analyzed within the study [11]. Jet has been visualized using Schlieren method in “Z” configuration. The stagnation pressure ratios (PR) of 2, 3, 4 and 5 have been examined. The analysis of jet evolution has been conducted, based on its tip – furthest point of the gas jet. Based on the results, in the early (transient) phase of the injection process, during the opening process, penetration is insensitive to nozzle pressure ratio. After the certain time, the velocity significantly rises when PR increased. Significantly shorter time to reach full registration length has been noted for increased PR. It is stated, that injection pressure impacts velocity of jet evolution, but the dependency doesn't show linear character.

As it was mentioned, the implementation of spark-jet ignition leads to the mixture inflammation on the way of

another mechanism than conventional spark ignition. On ignition mechanisms of methane/air mixture using a hot turbulent jet have been examined within the study [12]. Schlieren imaging has been coupled with OH* chemiluminescence to distinguish the inflammation mechanisms. Two characteristic processes have been found:

- ignition by a reacting jet (flame ignition),
- ignition by a reacted jet (jet ignition).

In the first mechanism, the flame with active radicals is being transferred into the volume of the main chamber. The second mechanism is being executed, when the hot products of pre-combustion are penetrating the main mixture. The flame is being extinguished while passing through the nozzle, due to the rapid cooling and/or high stretch rate. Both mechanisms show differences in the ignition delay. The inflammation with reacted jets is slower because quenched flame requires more time to be mixed with cold ambient while reacting jet consists intermediate species promoting chain branching reactions. The appearance of mechanism, and therefore the capability to ignition depends on combustion conditions in the ignition chamber and the nozzle parameters. With the increase of nozzle diameter, there is a tendency to flame ignition, while smaller orifice diameter tends to the ignition by reacted jet.

Combustion systems equipped with pre-combustion chamber are known since early 20th century when Harry Ricardo constructed two-stroke SI engine equipped with “bulb” type ignition chamber to provide benefits from the combustion of stratified charges [13]. Currently, combustion systems with ignition chamber are being used to provide enhanced ignitability of ultra-lean mixtures [14]. Within the mentioned study, combustion indicators and flame development in the combustion chamber have been analyzed for the operation of an optically accessible engine equipped with spark ignition, which has been replaced and compared with the turbulent jet ignition. The main chamber has been fed with gasoline in both research campaigns. Ignition chamber of turbulent jet ignition was fueled with gaseous fuel – propane. The stability of combustion has been accessed based on the CoV(IMEP). When the limit in cyclic variations $\text{CoV(IMEP)} < 5\%$ is assumed, the extension of lean-burn stable operation from $\lambda \approx 1.3$ to $\lambda \approx 2.0$ has been achieved. The rise of thermal efficiency has been confirmed, up to $\lambda \approx 1.8$. From this air excess coefficient value a drop of combustion stability has been noted. In terms of higher mixture dilutions (over $\lambda \approx 1.4$), a rapid drop in NO_x emissions has been noted.

Optical analysis has been conducted to determine the velocity of flame propagation, calculated from registered flame luminosity. With the rise of mixture dilution, the slower rise of the average flame radius has been noted, parallel with smaller flame luminosity. Comparing the images of combustion initiated with conventional and TJI, in terms of $\lambda = 1.4$ and $\lambda = 1.8$ retrospectively, it can be found, that similar luminosity of combustion initiated with TJI in advance, despite higher air excess. Based on the literature review it can be stated, that the intensity of chemiluminescence light correlates with heat release

rate [15]. Authors of mentioned study noted and confirmed, therefore, drop of heat release rate with the rise of air excess ratio. The faster burn rate of combustion initiated by hot jets has been also observed.

2 Research methodology

2.1 Test-stand and Schlieren setup

Research has been carried using the experimental optical method. To visualize the development of CNG jet in the transparent air environment, Schlieren method has been used and “Z”-type setup has been formed (as shown in Fig. 3).

Fig. 3. Optical research setup for Schlieren investigations.

According to the Fig. 3, presented optical setup is based on two parabolic mirrors (3) with diameter $d = 150$ mm and focal length $f = 750$ mm. The registration of the images has been performed using high-speed camera – LaVision HSS5 (1) with a monochromatic CMOS-transducer set on registration frequency of $r = 5$ kHz. The vertically positioned knife edge has been used to create horizontal Schlieren cut-off (2). Light beam has been generated using 40 cd LED (4) with a lens diameter $d = 5$ mm. The beam angle for this diode equals 15 deg. The diode has been coupled with a circular aperture (5). The visualization area is located between parabolic mirrors, where the collimated light stream is provided. In this area, Constant Volume Chamber (CVC) has been mounted to ensure chosen value of back-pressure during the injection. Parameters of the CVC used to the investigations are collected in the Tab. 1.

Table 1. Parameters of CVC.

Parameter	Unit	Value
Volume	dm ³	1.7
Maximal pressure	MPa	10
Material	–	Steel
Optical access	–	$d = 80$ mm, from 5 perpendicular directions
Charge control	–	solenoid valves
Heating system	–	yes, electro-resistive heater

On the top of the CVC, optically accessible ignition-chamber has been mounted. Some constructional parameters of this chamber are described in the further chapter.

2.2 Optically accessible ignition chamber

Ignition chamber is located in the upper part of the combustion system and is connected to the main combustion chamber. Its construction has to provide the possibility to supply fuel to the chamber (scavenged variant) and to deliver external energy necessary to the inflammation of mixture. This auxiliary energy can be transferred to the charge using spark plug or heating plug [16]. The investigation on the variant equipped with spark plug will be discussed within this study. The optically accessible model of such a chamber has been constructed (as shown in Fig. 3).

Fig. 4. Isometric CAD-model of optically accessible ignition chamber.

The main shape of the ignition chamber has been machined in the bottom part (no. 1, on the Fig. 3). Due to the implementation of optical access providing use of i. a. Schlieren method, the shape of this model represents an elongated cross-section through the base ignition chamber and provides an optical path (3). The upper part of the chamber (5) contains M12 spark plug (6) from the modern gas engine. Fueling of the chamber has been conducted using gas injector mounted in the slot (7). Mentioned injector slot is connected to the internal volume of the chamber with near-vertical ($\alpha = 3.5$ deg) channel ($d = 1$ mm) and check valve separating internal chamber volume from the fuel supply system. The internal volume of the chamber is restricted with quartz glass windows with thickness $g = 20$ mm. Components are sealed with PTFE-gaskets. The bottom part consists nozzles ($d = 1.5$ mm) providing mass transfer between interiors of main chamber and ignition chamber. The construction of chamber ensures the possibility to conduct the research on injection and acyclic combustion.

2.3 Scope of research and data analysis

Research has been carried to investigate the impact of the injection pressure (p_{inj}) and the pre-chamber back pressure (p_{ch}) on the mixture formation. The experiment to detect the impact of the first mentioned parameter on mixture formation has been conducted for three values of pressure p_{inj} measured upstream the injector:

- 5 bar abs,
- 7 bar abs,
- 9 bar abs.

P_{inj} was adjusted using pressure reducer mounted on the vessel with methane N35. The influence of the p_{ch} has been investigated in terms of injection to the chamber with atmospheric pressure and 2 bars overpressure. Raw images consist a monochromatic flat representation of the volumetric processes occurring in the pre-chamber. Two-dimensional images have been post-processed in the Davis software to amplify optical signal and reduce background noise. Images exported to a format compatible with Fiji ImageJ software have been converted to volumetric representation to provide better identification of a front of the gas jet and share of fuel-rich regions in the whole interior of the chamber (compare with Fig. 5a). The analysis of four operating points has been conducted, based on the traces of parameters calculated for jets tip, presented in the Fig. 5b.

Fig. 5. Extruded outline of cross-section through chambers interior (a), representation of jets vertical penetration L_y (b).

Regarding Fig. 5b, jets length L_y has been calculated from the jets furthest point y_{tip} and the horizontal top surface y_0 of the chamber's internal volume:

$$L_y = y_{tip} - y_0 \quad (2)$$

and resolved over time.

The point of fuel delivery is located on the horizontal top surface, on the side of spark plug's mass electrode (compare with Fig. 4). The velocity of jets tip has been calculated from the formula

$$V_y = \frac{dL_y}{dt} \quad (3)$$

where dt – time period between registration of two consecutive pictures, and resolved over L_y . It leads to the characterization of jets dynamics in relation to the position in the chamber.

Three main sources of uncertainty have been noted in this research:

- repeatability of injectors operation,
- the turbulent behavior of jet,
- post-processing uncertainty.

Fuel injector was operated using open, full-variable control system with steady temperature conditions and acyclic operation, it's high repeatability can be assumed. The impact of gas-dynamic phenomena has been reduced to repeating the operating points and calculation of mean value. However, the optical data has been presented from the single operating point. The uncertainty of post-processing depends on the definition of furthest point of registered density inhomogeneity.

This uncertainty has been rated as 5 pixels, what represents 1.7% of jets length in the middle of chamber vertical fulfillment.

3 Analysis of optical data

Based on the Schlieren-theory, the optical signal (shadows and enlightened areas) occurs when the local inhomogeneity lead to the refractive deflection of incident light and change in index n [17]. This change is observed in terms of temperature differences, pressure gradients or variations in chemical compositions. According to this study, Schlieren signal is positively influenced by the differences in temperature caused by the drop of CNG pressure. The further reason of occurrence of Schlieren-signal is placed in the gradients of pressure caused by the expansion of gas supplied with higher pressure compared to the pressure of charge air in the volume of the chamber. Jets development has been presented in the Fig. 6.

Fig. 6. The development of gas jet in the ignition chamber.

Series located on the left side (series A) has been registered in terms of chamber overpressure of 2 bars and 7 bars absolute pressure in the CNG rail. Series presented on the right side (series B) shows jets evolution under CNG-rail pressure increased to 9 bar abs. The image on the beginning of injectors control signal has been shown in the previous chapter and represents the outline of ignition chamber with spark-plug elements, which consists an obstacle on the way of expanding fuel. The first occurrence of the signal with luminosity differences has been marked as a timestamp 0. In this moment, a wider area of the chamber has been covered with fuel for the series B, where the CNG rail pressure was higher. From the analysis of pictures registered 0.8 ms later it can be stated, that in the case of series B fuel expands deeper in the horizontal direction, while comparable vertical penetration. It means intensified expansion of fuel in the area of the spark plug and the faster beginning of mixture formation in the spark gap volume under increased pressure in fuel supply. This character of horizontal penetration causes fuel-enriched regions occurring close to the wall of the chamber, which can be also observed in further steps. Comparing the total series of registered images, faster expansion in the volume of the chamber can be observed for the operating point executed under increased rail pressure. The bottom has been achieved in shorter time period. As it was mentioned, the intensity of Schlieren-signal is influenced by the pressure gradients. The regions of highly intensified luminosity have been identified, mainly in the top of chambers volume. The occurrence of these spots is combined with the constructional feature of the ignition chamber – organization of fuel supply. Additionally, this effect can be caused by the turbulent movement around the mass electrode of the spark plug. Next regions with identified higher luminosity are located in the middle and lower part of ignition chamber, where the area of horizontal chambers cross section becomes smaller. It leads to the rise of pressure combined with rise of flow velocity. The dynamics of gas jet expansion will be assessed in details in the next chapter.

4 Dynamic behaviour of gas jet in the chamber

The dynamics of gas jets motion has been assessed based on the position of the furthest point, which has been calculated from registered Schlieren-signal and named jets-tip. Vertical positions of this point, resolved over the time, have been presented in the Fig. 7a. Analyzing the diagram of injection into the chamber with atmospheric pressure under $p_{inj} = 5$ bar abs (blue line), the calculated time to reach the bottom of the chamber equals $t_b = 2$ ms. In the case of operating point with increased p_{inj} (green line), the time period to reach the bottom of the chamber was significantly shorter, while the early stage of injection shows comparable character. This situation finds the justification for intensified horizontal expansion in terms of increased CNG-rail pressure.

The rise of p_{ch} represents a real engine conditions in retarded moment of injection. Analyzing the data, significant changes in jets evolution (case marked with a red line on Fig. 7a) are observed – approximately 4.5 – fold longer time period is required to cover the chamber with expanding fuel. Similar to the atmospheric case, increased injection pressure (orange line) leads to shorter expansion time combined with a comparable vertical course jets development in the early phase. Location-resolved values of velocity have been presented in the Fig. 7b. The rapid rise of the V_y has been found in the initial phase of fuel expansion in the chamber. In the lower part of the chamber, lower V_y has been noted. The source of this drop can be the rise of chamber pressure in terms rapid expansion of additional mass into the volume of the chamber.

Fig. 7. Time-resolved vertical length of the gas jet (a) and distribution of vertical component of velocity over the position in the chamber.

Alternatively, the drop of supply pressure combined with wave-effect, but to confirm this phenomena research including fast analysis of pressure in fuel supply is required. Higher velocities of the jets tip have been calculated for the injection into the lower p_{ch} due to the smaller density of ambient charge and therefore smaller static mass breaking the expanding gas. Independently from chamber back-pressure, increased p_{inj} resulted in shifted (for later) point of maximal velocity. In the lower part of the chamber (17 mm of distance from the fuel supply point), the slower drop of the velocity has been noted. This has a connection with the issue identified on optical data and finds its justification in the convergent construction of lower part of the chamber causing the increase in pressure and expansion velocity.

5 Summary and conclusions

Within the study, the optical research method has been applied to the mixture formation analysis in the ignition chamber of the spark-jet ignition system. The applicability of the Schlieren method in “Z”-configuration to the research on injection of gaseous fuel into the ambient air has been confirmed. Based on the optical data, the parameters of jets tip have been calculated and dynamics of gas expansion in the chambers internal volume has been assessed. The impact of both chamber back-pressure and pressure in fuel supply system on the mixture formation has been evaluated. Shorter time to cover the chamber volume with fuel, promoting better homogenization of mixture has been found in terms of increased pressure in fuel supply. The regions of intensified motion of the charge have been identified.

The research can be continued and complemented by the fast measurement of pressure in the fuel supply system, and its analysis to understand better the impact of gas-dynamic phenomena on mixture formation.

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