Flame propagation velocity in 2-stage gas combustion system applied in SI engine

W Bueschke  M Skowron  F Szwajca and K Wisłocki
Poznan University of Technology
Piotrowo Street 3, 60-965 Poznan
E-mail: wojciech.bueschke@gmail.com

Abstract. Ever stronger emission standards accepted for modern internal combustion engines force some new tendencies in the engine development trends. In recent studies it was confirmed, that the use of combustion of lean gas-air mixtures leads to reduction of CO₂ and HC emissions while maintaining a possible acceptable value of thermal efficiency. Such combustion systems, already known since many years as e.g. Turbulent Ignition, Pulsed Jet Combustion, Sparking Jet Ignition and similar, can offer further potential in the improvement of combustion process control. The main purpose of this research was to detect and define any correlation between gas delivery parameters, ignition energy in the first stage of combustion and some system design parameters with the turbulent ignition possibilities of lean and very lean gas mixtures, with the flame propagation velocity in main chamber and with the intensity of heat release. Such correlation should deliver some answers for the combustion system optimization and better combustion process control.
For the above mentioned purpose the test stand with the model of IC engine was adopted. It delivered the possibilities of the spark-plug ignition in the prechamber and of the dynamic observation of the ignition spray propagation in main chamber of the system. For this last task the Rapid Compression Machine has been applied equipped with the optical access into main chamber and with high-speed recording system for dynamic registration of spray formation as well as for flame propagation across the chamber. Simultaneously performed indication of both chambers (pre-chamber and main chamber) made it possible to correlate of indexes determined for flame propagation velocity, flame luminosity distribution in main chamber with thermodynamic indexes achieved form the analysis of the pressures, temperatures and mixture masses in both chambers.
The results achieved within this research allow to identify many design parameters of the 2-stage combustion system and to recognize more important thermodynamic parameters of the system which seems to be essential for improving of the system potential according heat release, heat release rate and system thermal efficiency for the future development.

1. Introduction
The lean burn gas-air combustion systems are currently being considered as a ones of the most promising combustion systems in terms of their efficiency and emission factors. However, in lean combustion systems it is intended to use more powerful ignition systems due to the demand on ignition energy rising with increased mixture dilution. The solution providing bigger ignition energy is turbulent jet ignition, which can be applied to the combustion systems of different fuels or even the combination of them (distributed between PC and MC) also in gaseous state of matter [1]. Turbulent jet ignition consists of prechamber (PC) providing pre-combustion event and generating igniting jets transferred to the main
chamber (MC). The higher grade complexity of such a system requests additional investigations to adjust the values of regulatory parameters and constructional features, comparing to the conventional spark ignition.

The nozzle diameter has been optically investigated using rapid compression machine [2]. The 1.5, 2.0 and 3.0 mm nozzles have been compared for the combustion of propane/air mixture without additional injection into the prechamber. Smaller diameter orifices tend to shorter time period of 0-10 % mass fraction burned (MFB), which is resulted with mass transfer from ignition chamber under higher velocity and faster flame initiation. Qualitative flame assessment allow to note, that smaller orifice diameter provide bigger jets turbulence promoting inflammation. The 10-90% MFB is significantly and positively impacted by orifice diameter reduction in lean conditions due to the intensified jets propagation. The length of the nozzle was also investigated for the range of 3…7 mm [3]. It has been found, that with increase in cavity depth the cylinder pressure is being increased. Further improvement has been discovered from the comparison of dual nozzle prechamber to single nozzle basic configuration done by Chinnathambi et al [4]. The optical measurements of CNG combustion in RCM confirmed intensified flame development in the main combustion chamber for bigger number of nozzles.

The conditions in the main combustion chamber affect the operation of prechamber ignition system. The temperature is an important factor for the occurrence place of combustion source [5]. It has been noted, that the distance achieved by the active radicals transferred from the pre-combustion chamber at the defined time instance is being reduced with increase in cylinder temperature. As the results of this numerical study deliver, at 300 K jet of the active radicals achieve the length of approximately 65 mm, while at 700 K only 10 mm at the same time. The combustion starts closer to the nozzle, while the temperature is being increased. The pressure inside the combustion chamber impacts the combustion parameters significantly [6]. In the mentioned study ignition delay has been investigated using RCM in terms of lean combustion and chamber pressure variation between 105 and 160 bar. The positive correlation between ignition delay reduction and pressure increase has been found, as a consequence of intensified chain termination reaction.

The on-ignition from the igniting jet can take place depending on two main mechanisms- from reacting jet and from reacted jet [7], which have been identified using Schlieren- and OH* chemiluminescence imaging of \( \text{CH}_4/\text{air} \) combustion. Both mechanisms differ in terms of their course- flame ignition takes place on the entire jets surface and is faster than jet ignition, which starts more from the lateral sides. The effects of following parameters on the on-ignition even have been investigated: nozzle diameter (2.5…4.5 mm), initial pressure (0.1…0.4 bar) and main chamber equivalence ratio (0.5…1.0). Reduced nozzle diameter tends to higher stretch-rate of prechamber flame, its quenching and jet ignition, while bigger nozzle oppositely – flame ignition. Bigger pressure in the chamber promotes flame ignition mechanism. The equivalence ratio inside main chamber impacts probability of ignition occurrence, however in investigated static conditions (constant volume chamber), influence on igniting jet has not been noticed. Another study [8] focused on the measurements in dynamic conditions using RCM discovered strong dependency of main combustion and also pre-combustion on initial main chamber mixture due to the charge transfer in compression stroke preceding pre-combustion event.

The turbulent jet ignition has been also applied and tested in consecutive combustion conditions as confirmed in various publications [9][10][11][12]. However, due to the complexity of dependencies between constructional features and control parameters with combustion course further investigations are necessary in order to describe them in the volume instance and understand better, what consist the goal of this study.

2. Scope of investigations and test setup

The influence of following parameters on combustion course has been investigated:

- the angle of nozzles,
- start of ignition,
- the quantity of prechamber injection.
Measurements have been performed using rapid compression machine, which uncontinously executes the cycles of combustion and provides optical access into the combustion chamber in combination with indicating measurements (Fig. 1).

The piston movement is initiated pneumatically (typ. driving pressure 37 bar) and connected to the crank mechanism (invisible in Fig. 1.) ensuring its repeatable track over the sequence. The charges flows through the driving chamber and the combustion chamber were being controlled using fast solenoid valves. Piston crown has a built-in 50 mm diameter quartz glass window to optical investigations of combustion and in its middle way the flat-plane mirror creating the optical path to the camera (LaVision High Speed Star 5 for up to 250 kHz recording rate). The adjustment of activating signals for the components of RCM test-bench is being conducted using Sequencer. The used adjustable ignition system varies the coil charging strategy in time, providing the peak primary current up to 12A. The gas engine coil and spark plug have been assembled in cylinder head, as well as electromagnetic direct injector fuelled with Methane N35 under the 8 bars of pressure.

The parameters mentioned on the beginning of this chapter have been assessed quantitatively and qualitatively based respectively on the indicating measurements and optical data, which has been also parametrized. From the cylinder pressure $P$ and the operational chamber volume $V$, heat release rate $\frac{dQ}{dt}$ has been determined using following dependency:

$$\frac{dQ}{dt} = \frac{\kappa}{\kappa - 1} \left( \frac{P_t + P_{t+1}}{2} \right) (V_{t+1} - V_t) + \frac{1}{\kappa - 1} \left( \frac{V_t + V_{t+1}}{2} \right) (P_{t+1} - P_t)$$

where $\kappa$ is an isentropic coefficient.

The images recorded using the camera have been post-processed using LaVision Davis software to filter the background noise influencing negatively analysis. From the entire captured area, the optically accessed part of combustion chamber has been extracted and analysed. For this regions, the mean luminescence of the flame $I_{\text{mean}}$ has been determined. In case of igniting jets development, its velocity has been calculated as

$$v = \frac{l_{t+1} - l_t}{\frac{1}{f}}$$

Where $l$ is the jets length in the selected time instance, $f$ – recording frequency. The parameters of RCM test-bench are collected in the Table 1.
Table 1. Parameters of rapid compression machine

| Parameter                        | Value/Type      | Unit  |
|----------------------------------|-----------------|-------|
| Propulsion                       | Pneumatic       | -     |
| Cylinder displacement            | 437             | cm³   |
| Bore                             | 80              | mm    |
| Stroke                           | 87              | mm    |
| Compression ratio                | 14.2            | -     |
| Cylinder pressure transducer     | AVL             |       |
| Displacement of ignition chamber | 1.83            | cm³   |
| Nozzles: number/orientation      | 7/tangential-twisted | -     |
| Prechamber injecting valve       | Electromagnetic |       |

For the investigations at the defined value of air-fuel equivalence ratio, the fuel quantities injected to the prechamber and the main chamber have been so adjusted, too.

3. Investigation results
The research into start of pre-ignition has been conducted and the parameter was being controlled with variation in start of signal occurrence in pre-circuit of ignition coil. This part of the study has been performed to analyse the course of main combustion process in terms of change in pre-combustion events course. Combustion cycles have been recorded for two points different for 1.4 ms in terms of pre-ignition occurrence (Fig. 2).

![Figure 2. Flame propagation for the and 1.4 ms advanced ignition (red line)](image)

According Fig 2a the combustion under advanced ignition indicates faster development of the igniting jets (pictures captured 2 ms after SOI), often with biggest heat release rate in the centre of the jets. The auxiliary layers transfer the heat with unburned fuel fraction, what causes its reduced luminescence. Calculated mean luminescence intensity (Fig. 2b) shows bigger luminescence and reaction rate for advanced ignition, which is however observed up to 14 ms after SOI. The last 4 ms are being dominated by the retarded ignition, what allows to state, that ignition advance provides intensified and shorter time period of combustion duration, what has been than analysed using cylinder and prechamber pressure signals (Fig. 3).
Figure 3. Pressure traces for base ignition point (green line) and 1.4 ms advanced ignition (red line)

The advanced ignition (Fig. 3, red line) indicates advanced occurrence of rapid pressure increase (expected) and bigger value of cylinder pressure. The same tendency can be observed for the combustion process occurring in the ignition chamber. From the detailed analysis in pre-chamber pressure history it can be noted, that bigger pressure increase during pre-combustion event occurs when the ignition is being advanced. This have a reflection in aforementioned bigger heat release of the igniting jets transferred from pre-chamber, which have been optically indicated.

The impact of nozzles orientation has been investigated using scavenged variant of prechamber system and at $\lambda=1.3$. The tangential nozzles have been compared to the nozzles tilted for 20 deg in the horizontal plane. The flame development inside main combustion chamber has been visualized (Fig. 4).

Figure 4. Flame development for tilted (top) and straight (bottom) nozzles

According to the Figure 4, the images represent the flame luminescence spectra inside MC over the time after introducing the ignition signal (constant for both nozzle orientations) and for 8 time instances in unlinear scale adjusted to the occurrence time of captured phenomena. Big value of luminescence confirms big grade of ignition mechanisms from the reacting jet. The view of igniting jets at 0.36…0.72 ms indicates more luminescent optical signal, which is combined with bigger intensity of reactions in the flame area [13]. It is stated, that this is combined with bigger complexity of charge movement preceding combustion inside prechamber, which cause bigger heat release rate and therefore intensified development of igniting jets at the initial stage. However, despite the delayed early flame propagation, the jets developing radially indicate bigger interaction with cylinder wall and faster reversed propagation of the jets to the combustion chamber (1.32 ms) with their faster connection and more luminescent flame around the accessible chambers area. Cylinder pressure history has been also analysed (Fig. 5).
Analysing the cylinder pressure history (Fig. 5a), the 1.5 ms delay in the rapid increase in cylinder pressure can be noted, when using the prechamber with radially oriented nozzles, which however provided bigger peak-value of cylinder pressure. The increased rate of heat release (Fig. 5b) using radial nozzles has been found.

The impact of prechamber scavenging strategy has been investigated optically for the operating point with $\lambda=1.3$. Based on the recorded images, the igniting jets velocities and their mean luminescence intensity have been calculated (Fig. 6).

The jets development at the early stage indicates biggest expansion velocity (Fig. 6a), up to 90 m/s in case of bigger prechamber injection (1.67 mg), which drops in the consecutive time instances. The occurrence of massive development fluctuations, reaching 30 m/s in the subsequent measurement intervals, suggests wave-phenomena inside the ignition chamber or significant inhomogeneity of main mixture composition inside the main combustion chamber. However, the injection process to the main combustion chamber is being performed before the piston movement sequence is being launched, what is combined with seconds-long mixing time, better dispersion of fuel in the air and therefore improved mixture homogenisation than possible to reach in real engine conditions. This suggests gas-dynamic phenomena, which should be separately investigated in details. The jets velocity in case of $q_{PC}=0.79$ mg is tending to 370 µs after the beginning of jets transfer to the main chamber, while igniting jet generated for $q_{PC}=1.67$ mg reaches the optically accessible area 58 µs later. Taking into account also
the smaller luminescence of the flame recorded in this case (Fig. 6b) it can be stated, that the fuelling of the prechamber met its limitation in terms of fuel injection to the prechamber causing small air-fuel equivalence ratio of the mixture and reduced reaction rate.

4. Summary and conclusions
The research into lean charge combustion in split-chamber system using RCM has been performed for variation in:
- start of ignition,
- fuel mass injected to the prechamber,
- angle of the nozzles.

The start of ignition advanced for 1.4 ms resulted in intensified pre-combustion process in terms of the prechamber overpressure generated during this event, which led to the faster expansion of the igniting jets in the main chamber. The further combustion stages indicated also bigger flame luminescence and heat release rate.

Combustion using straight nozzles indicated elongated induction phase of combustion in comparison to the combustion initiated with prechamber with twisted nozzles. However, after the combustion initiation, the heat is being released more intensive and bigger maximal pressure in the cylinder is being reached. This has an source possibly in earlier occurring jet-wall interaction, further split of the jet, its orientation on adjacent jet, finally splicing and intensified covering the combustion chamber with flame.

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