Rate of Heat Release and Flame Speed in Premixed Charge Combustion in a Rapid Compression Machine with and without Prechamber

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Abstract
In this study the possibility of using RCM to simulate prechamber gas engines was under investigation. The main effort was focused on pressure trace analysis and high speed flame visualisation. Rate of heat release and flame speed were used as indicators of the combustion process dynamics. The results show that the prechamber broadens the operating range of the RCM in every studied aspect. In case without prechamber the flame exhibits features of laminar flame making the combustion process prolonged. The prechamber in turn, compensates very low turbulence and therefore makes the RCM suitable for simulating prechamber gas engines.

Introduction

Rapid compression machine (RCM) with its over one hundred years history has been well established as efficient research tool for combustion related studies. The biggest application area of the RCM is related to ignition delay studies [1–5]. The RCM intended for such research is desired to have a feature of keeping the piston at TDC (top dead centre) after the compression stroke. However, RCM can serve as a tool for simulating engine work, providing convenient optical access for in-cylinder processes observation. Then, the RCM should include expansion stroke as well. In this study the focus was on RCM with expansion stroke. While most studies on RCMs employing expansion stroke are focused on spray development in engine relevant conditions, spray autoignition [6,7] and diesel combustion, the spark ignition in-cylinder processes are usually studied on single cylinder optical engines. Pöschl and Sattelmayer [8] studying knocking characteristics of premixed iso-octane/n-heptane/air mixtures observed charge temperature stratification. This led them to conclusion that after charging of the machine, turbulence decays quickly and the motion of the piston during compression does not produce substantial turbulence [8]. Their finding shows that conventional RCM cannot fully represent the condition present in SI engines, specifically in terms of turbulence. In this study the possibility of using RCM to simulate prechamber gas engines was under investigation. The prechamber is expected to overcome the issue of initially low turbulences in the RCM chamber at the start of ignition (SOI) by momentum exchange between the reacting jets outgoing from prechamber and the gas in main chamber.

The main effort was focused on pressure trace analysis and high speed visualisation of the flame. Flame speed and rate of heat release were used as indicators of the combustion process dynamics. Rate of heat release was calculated basing on recorded pressure trace. Flame speed was determined by high speed imaging in visual range of wavelengths.

The research was conducted in two parts. The first part of the study was focused on stoichiometric mixtures. At this stage two cylinder head arrangements (with and without prechamber) were tested and compared. The major aim of this part was to prove the assumption that the prechamber will increase the combustion process dynamics by increasing turbulences in the main chamber.

The second part of the study was aimed at testing the performance of the RCM in prechamber setup for lean mixtures and proving capability of operating in extended range of equivalence ratio. At this stage the prechamber setup was tested using two different fuels, methane and ethane.

Experimental Setup

The tests were conducted on pneumatically driven RCM employing expansion stroke. The RCM used in this study is not equipped with a crankshaft mechanism typical for IC engine. The piston movement is caused by compressed air, which is collected in the driving gas volume. The gas present in the driving gas volume pushes the equalizing piston which is connected with a piston tube by hydraulic coupling. Equalizing piston is the element which is responsible for balancing the inertia forces of the piston and piston tube by moving to the opposite direction what prevents vibration of the machine during the tests. The RCM in these research was used to investigate premixed combustion using spark ignition. Therefore the RCM was equipped with spark ignition system which allows to set ignition timing according to the piston movement (at specified piston position). RCM allows to set many parameters during the tests. The parameters which can be set are as follows:

- Stroke – range from 120 to 250 mm
- Driving gas pressure – range from 0 to 7 MPa
- Charge pressure – from 0 to 1 MPa
- Compression ratio in a very wide range which depends on stroke, driving gas pressure and charge pressure
- Temperature of the cylinder – range from ambient to 120°C
- Temperature of the piston – range from ambient to 100°C

More information on the RCM design can be found in [8,9]. The view of the test bed with the RCM used in this study is shown in Fig. 1.

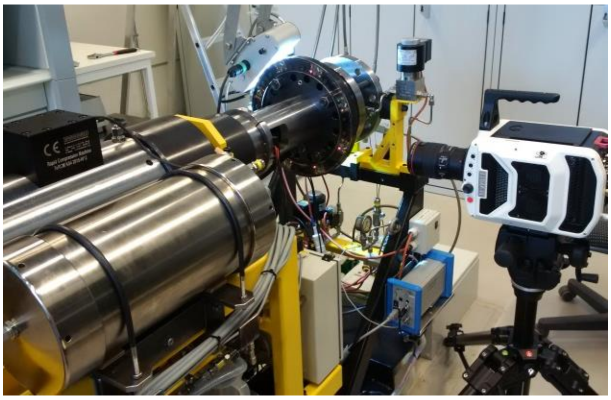

Fig.1. View of the experimental setup and the RCM.

In order to increase in-cylinder charge air temperature at bottom dead center (BDC), both top part of the cylinder, called visibility ring, and the piston were equipped with electric heaters. The desired mixtures were created on a partial pressure basis inside the RCM chamber. Air and fuel were delivered to the RCM by separate ducts through electromagnetic valves. To ensure proper values for the driving gas pressure, charge pressure, in-cylinder temperature RCM was equipped with pressure sensors installed in the supply ducts and thermocouples installed in the visibility ring and in the piston crown. The pressure sensor used for mixture preparation was Wika A-10, range from 0-1 MPa (absolute).

In-cylinder pressure during combustion was measured by piezoelectric Kistler pressure transducer installed in the cylinder head.

Modular construction of the RCM cylinder and cylinder head allows to make fast changes of the visibility ring from normal to one with transparent quartz windows, of the piston from normal to one with visibility window and of the cylinder head from flat type to design with prechamber.

In this study two types of cylinder head were used, flat cylinder head and cylinder head with prechamber. The upper part of the cylinder (visibility ring) and the piston were in versions with transparent inserts which allowed to record ignition and combustion event with high speed camera.

As mentioned earlier, in this study two different gases were tested, methane and ethane. The aim of that was to limit the possible fuel specific effect on RCM operation.

The research was conducted in two stages. At the first stage of the study the RCM was tested on stoichiometric mixtures for the same charge air pressure of 0.2 MPa (absolute) and driving gas pressure which was of 1.5 MPa (absolute). The same pressure values in all cases resulted in similar compression ratio. The exact values of compression ratio and other parameters in each case are shown in Table 1.

Table 1. Measurement points for stoichiometric mixtures.

Case	**Fuel**	**Cylinder head type**	**Ignition occurrence / mm after BDC**	**Compr. ratio**
Case 1	Methane	Flat head	150	11.2
Case 2	Methane	Flat head	150	11.3
Case 3	Methane	Prechamber	150	11.5
Case 4	Methane	Prechamber	150	11.2
Case 5	Methane	Flat head	165	10.8
Case 6	Methane	Flat head	165	11.2
Case 7	Methane	Prechamber	165	12
Case 8	Methane	Prechamber	165	12.3
Case 9	Ethane	Flat head	165	11.3
Case 10	Ethane	Flat head	165	11.2

The second part of the study included tests only with prechamber setup for lean mixtures. At this stage, two different fuels were tested, methane and ethane. The measurement points in second part of the study are shown in Table 2.

Table 2. Measurement points for lean mixtures (prechamber only).

Case	**Fuel**	**Ignition occurrence / mm after BDC**	**Compr. ratio**	**Equiv. ratio**
Case 11	Methane	150	10.9	0.66
Case 12	Methane	150	11.2	0.66
Case 13	Ethane	150	10.2	0.5
Case 14	Ethane	150	10.6	0.5

Results

At the beginning the RCM was tested on stoichiometric mixtures in order to compare prechamber setup with conventional flat cylinder head (Cases 1-8). The test conditions for these cases are shown in Table 1. In the first two cases (Cases 1-2) the mixture didn't ignite at all. When the cylinder head was replaced with the one equipped with prechamber, the mixture ignited easily, and resulted in high peak pressure (Cases 3-4, shown in Fig. 2). As a next step, for the setup without prechamber the ignition timing was delayed so the ignition occurred just before TDC (top dead centre) when the temperature of compressed mixture becomes very high. In these in-cylinder conditions it was possible to ignite the mixture. However, the combustion process was prolonged and the main pressure rise caused by combustion process took place when the piston was far after TDC. The characteristic bumps on ascending slope of pressure curve as a result of prolonged combustion are shown in Fig. 2 (Cases 5-6). For comparison purposes the same ignition timing was applied for setup with prechamber (Cases 7-8). The main pressure rise was also a bit delayed but it appeared much earlier than in cases without prechamber (around 20 ms earlier). The pressure traces for Cases 3-8 are shown in Fig. 2.

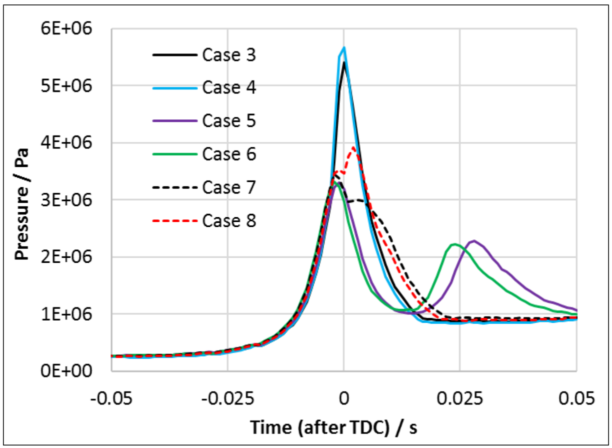

Fig. 2. Pressure traces for Cases 3-8.

The recorded pressure traces were analysed in terms of rate of heat release (ROHR). The calculations were based on the assumption of uniform pressure, density and temperature in the cylinder and on the assumption that adiabatic index remains constant during the compression stroke. ROHR was calculated as gross value including heat losses to the surrounding walls (the adiabatic index was calculated for tested mixtures). These assumptions could not be used for comparison of the results from different devices but for rough comparison of the results obtained on the same device with similar compression ratio such approach was sufficient.

The ROHR curves for Cases 3-8 are shown in Fig. 3. The maximum values of ROHR were very similar in all 6 cases (Cases 3-8). However the initial stage of the combustion process was substantially different depending on the cylinder head type. In cases without prechamber (Cases 5-6) the initial rate of heat release (from 0 to around 0.015s) was of order of magnitude lower than the observed maximum value. Moreover, this stage took as much time as almost whole combustion process in cases with prechamber (Cases 3, 4, 7 and 8).

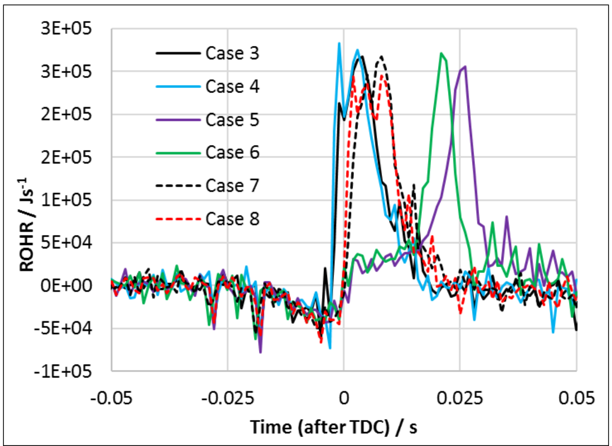

Fig. 3. ROHR curves for Cases 3-8.

Additionally to the collected pressure traces, the combustion process was observed by the high speed camera. Visualised flame for the case where prolonged combustion was observed (Case 6) is shown in Fig. 4, while for prechamber in Fig. 5. The images were selected arbitrarily to show the whole propagation process in 4 frames and thus the time step between the selected frames was case dependent. In Case 6 it was 5 ms, while in Case 4 – 2 ms.

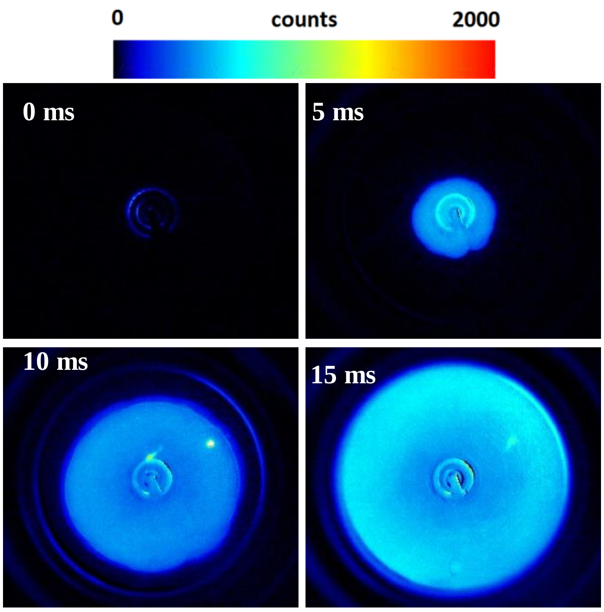

Fig. 4. Visualised flame for Case 6 at instance of ignition and 5, 10 and 15 ms after ignition.

The observed flame in Case 6 exhibited laminar flame features. As shown in Fig. 4, the visualised flame was a spherically expanding type flame without any visible surface deformation, what indicates no large scale turbulences capable to wrinkle the flame. The only large scale deformation on the flame surface which can be seen was caused by the spark electrode and it was present at the flame front through the whole flame propagation process.

The flame propagation process in case with prechamber (Case 4) is presented in Fig. 5. One needs to be aware that the time step between the selected frames was different than in case without prechamber. As expected, the visualised flame in case with prechamber behaved in a completely different way. First, reacting jets penetrating the main chamber could be seen. The jets immediately reached the cylinder wall. Then, the flame propagated from the jets towards the surrounding unburnt mixture. This process was much faster than the combustion process without prechamber – the flame covered the whole visible area much faster. The combustion process in case with prechamber was much more intensive in other aspect. The emitted light intensity was much higher than in case without prechamber.

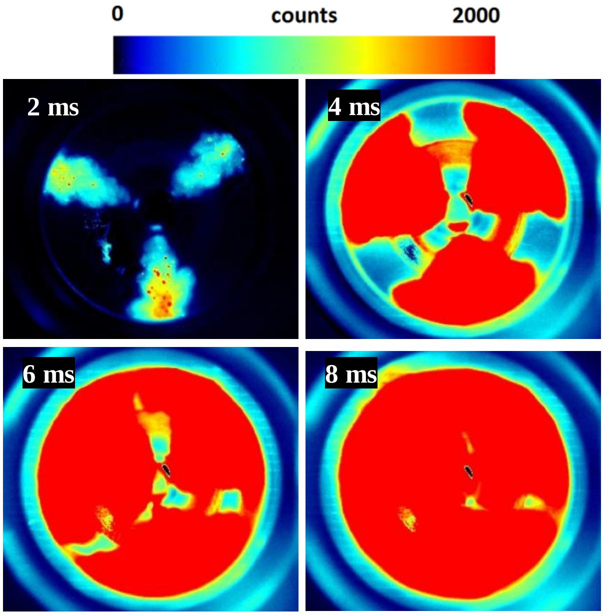

Fig. 5. Visualised flame for Case 4; images taken 2, 4, 6 and 8 ms after ignition.

Additionally to tests with methane, the tests on ethane (Cases 9-10) were performed for setup, with flat cylinder head. For ethane the combustion process was progressing much faster than for methane. In these cases the ignition timing was the same as in Case 5 and 6. Here the combustion process was also prolonged but the observed bumps on pressure curve appeared much closer to TDC (Fig. 6). The range of the plot axis was deliberately kept the same as in previous plot for convenient comparison of the cases.

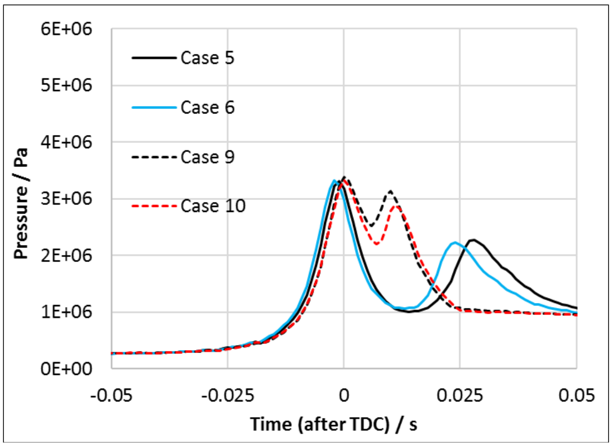

Fig. 6. Pressure traces for setup without prechamber; Cases 5-6 – methane, Cases 9-10 – ethane.

Faster combustion process resulted in higher ROHR peak. ROHR curves for ethane cases are shown in Fig. 7. For comparison purposes the graph includes also the results obtained for methane cases. Both the pressure curves and ROHR curves for methane and ethane could be compared directly since the energy contained in the stoichiometric mixture at the same conditions is very similar for these two gases.

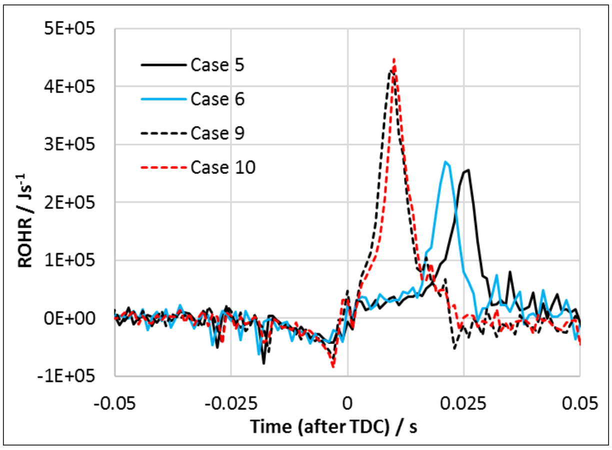

Fig. 7. Pressure traces for Cases 3-8.

Ethane flame was also a spherically expanding flame without visible local flame curvatures. The flame however reached the visible area limit much faster than in case of methane. The visualised ethane flame in case without prechamber (Case 2) is shown in Fig. 8.

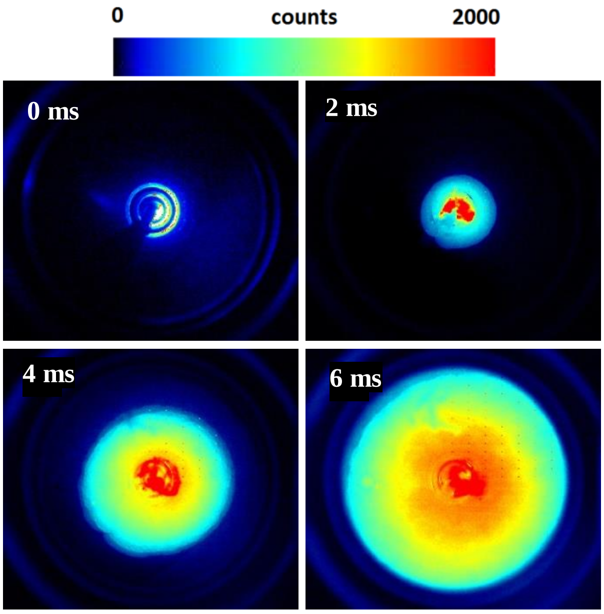

Fig. 8. Visualised flame for Case 2; images taken 2, 4, 6 and 8 ms after ignition.

For all cases where spherically expanding flame was observed, the average flame radius was determined (for both tested fuels). The image processing was done using LaVision DaVis v.8.4 software. The evolution of the average radius was plotted in Fig. 9. This concerned all flat head tests, where combustion occurred (Cases 5, 6, 9 and 10). Additionally, the equivalent radius was determined for one case with prechamber for the same conditions (Case 4). Equivalent radius was assumed to be the radius of a circle with the same area as the area covered by the flame. The light intensity corresponding to the flame border was set to 250 counts for all cases taken into account.

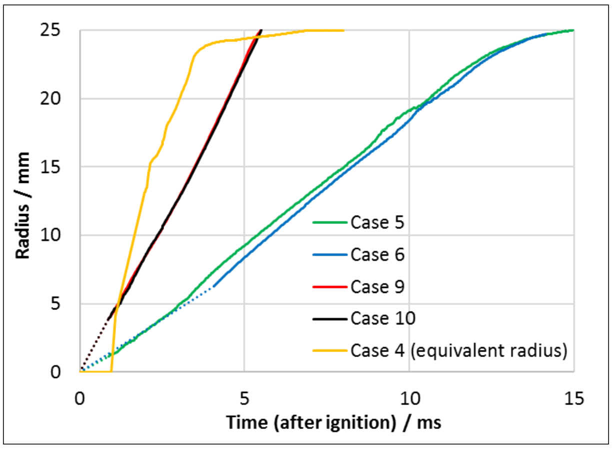

Fig. 9. Flame radius evolution; Cases 5, 6, 9 and 10 – flat head, Case 4 – prechamber (equivalent radius).

One needs to be aware that the equivalent radius does not need to reflect the volume of the burnt gas as the radius of a spherically expanding flame does. However, it might be a useful parameter for rough comparison of a combustion dynamics.

In cases without prechamber (Cases 5, 6, 9 and 10) the relation is almost linear indicating constant flame speed, which is higher for ethane cases (Cases 9-10). In case with prechamber the initial fast growth of equivalent radius is caused by outgoing reacting jets, which immediately reach cylinder walls (see Fig. 5 – first image). After that, the equivalent radius increase becomes slower. The jets reach the cylinder walls and the flame propagates only in perpendicular direction to the jet axis - jet angle increases. Even in that stage of the flame propagation the equivalent radius increases much faster than for any case without prechamber (even for ethane). This clearly indicates positive influence of the prechamber on combustion dynamics of premixed mixtures in RCM. At the just after ignition stage the flame ignites and propagates in prechamber. Since there was no optical access to prechamber, no flame was visible, and the equivalent radius was defined as 0.

The first part of the study showed that the prechamber setup provides reliable ignition and much faster combustion. The positive influence of the prechamber on combustion dynamics was confirmed by a flame radius growth comparison. Therefore the prechamber setup was tested later on lean mixtures. Two gases were tested at this stage, methane (Cases 11-12) and ethane (Cases 13-14). As shown in Table 2, the ignition timing was set to occur at piston position of 150 mm after BDC. One needs to be aware that for that conditions such mixtures with flathead design wouldn't ignite at all.

In all these cases the combustion process resulted in high peak pressures appearing just after TDC (Fig. 10). Maximum high pressure very close to TDC suggests that the ignition occurred too early. The ignition timing however was not the aim of the study and will be the subject of future tests. Moreover, one needs to be aware that the crankless design of the RCM behaves differently to conventional crank mechanism.

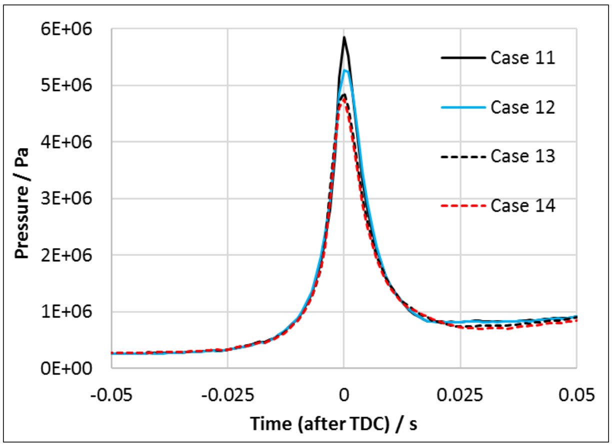

Fig. 10. Pressure traces for lean mixtures for setup with prechamber; Cases 11-12 – methane, Cases 13-14 – ethane.

As shown in Table 2, the equivalence ratio for cases with methane (Cases 11-12) and ethane (Cases13-14) was different. Therefore the energy contained in air-fuel mixture was different as well. That is why the pressure curves should not be compared directly. The pressure curves were however put together on one plot to show that combustion dynamics does not differ much for ethane and methane in prechamber setup.

For both fuels the combustion process duration was very similar. This can be clearly seen on ROHR curves shown in Fig. 11.

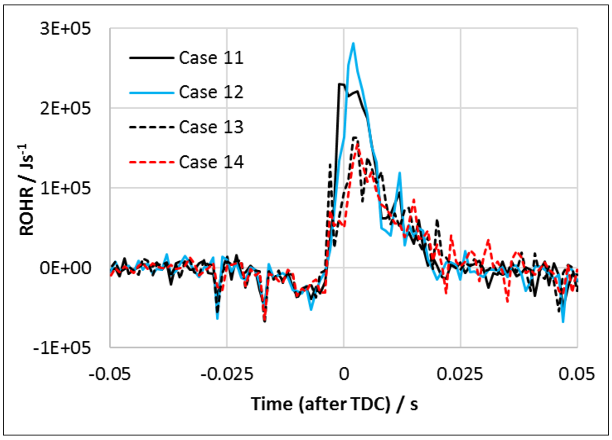

Fig. 11. ROHR for lean mixtures for setup with prechamber; Cases 11-12 – methane, Cases 13-14 – ethane.

The same combustion process duration for two different fuels suggests that in case of prechamber the turbulences, which are significantly increased comparing to design without prechamber [10,11], play the major role in the combustion process dynamics.

Summary and Conclusions

The aim of this study was to investigate the possibility of using RCM to simulate prechamber gas engines. For this purpose in-cylinder measurements were conducted using high frequency pressure transducer and high speed camera. Pressure traces were used to determine ROHR, while the captured images were used to determine the flame propagation evolution. The study was done in two stages. First stage was focused on stoichiometric mixtures and was basically aimed at proving that the prechamber design can overcome initially low turbulences at the instance of ignition.

Results obtained in the first stage proved the positive influence of prechamber on the ignition reliability and on the combustion process dynamics. The prechamber made possible to ignite the mixture with early ignition timing. Moreover, the combustion process itself progressed much faster. In cases without prechamber the observed flame exhibited laminar flame features. It was spherically expanding without surface deformation. The only deformation on the visualised flame surface was caused by spark electrode and it was present at the flame front through the whole flame propagation process in visible area. The conservation of this distortion during the flame propagation indicated low turbulences in the chamber for flathead setup. This is in accordance to Pöschl and Sattelmayer [8] findings who observed that after the machine charging, the turbulence decays quickly and the motion of the piston during compression does not produce substantial turbulence [8].

The prechamber design was expected to overcome this issue. When compared Figs 4 and 5 one might see that in case with prechamber the flame covered whole visible area much faster and the emitted light intensity was much higher than in case without prechamber. The ignition timing was different in these cases but as explained earlier the mixture for Cases 1 and 2 where the ignition timing was the same didn't ignite at all. Nevertheless, the results were shown in reference to start of ignition. The whole evolution of the flame front (shown in Fig. 10) leads to the same conclusions. The only questionable element is the bent of the equivalent diameter (Case 4) at around 4 ms after SOI. The reason for this could be related to the visible gaps between the flame jets shown in Fig. 5 which are still present 6 ms after SOI. Basing on that observation one might argue if the number of holes in prechamber should be increased. In general the results obtained in the first part of the study proved that the prechamber setup provides reliable ignition and much faster combustion.

The second part of the study was focused on investigation of the combustion process dynamics in prechamber setup for lean mixtures. At this stage two different fuels were tested, methane and ethane. Considering two different fuels was aimed at limiting the possible fuel specific effects on RCM operation.

The results obtained in this part showed very similar duration of the combustion process (Fig. 10) for both tested fuels. This observation suggests that the major effect on combustion process dynamics in prechamber setup is produced by the turbulences created by the outgoing reacting jets which at the same time constitute the ignition source of high surface area for the mixture present in the main chamber.

In general the results of the study showed that the prechamber broadens the operating range of the RCM in every studied aspect. In case without prechamber the flame exhibits features of laminar flame making the combustion process prolonged. The prechamber in turn, compensates very low turbulence (compared to engine) and therefore makes the RCM suitable for simulating prechamber gas engines.

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