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COMBUSTION PROCESS VISUALISATION IN RAPID COMPRESSION MACHINE MODELLING COMBUSTION IN SPARK IGNITION ENGINES

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Abstract

Mixture preparation and combustion processes in internal combustion engines are very complex and very difficult to investigate. These processes run very quickly and their parameters are changed quickly and in wide ranges. Therefore, the interpretation of measurement results is very difficult and uncertain. The visualization methods applied in the combustion researches can help to interpret the results. For many years, the visualization methods have been developed at the Aircraft Engine Department of Heat Engineering Institute of Warsaw University of Technology, in the field of combustion in engines, detonation and gas dynamics research. In these researches, different method of registration of very fast changes of combustion were applied. The combustion experiments have been performed in constant volume bomb, rapid compression machines and experimental visualisation engines. In the last case, the electronic digital camera of Photram SA 1.3 has been used. This paper refers to the experiments, which were conducted using rapid compression machine. Their goal was explanation the combustion mechanism in combustion system with semi-open combustion chamber under different parameters of this system. The obtained results show a strong influence of combustion system parameters on combustion mechanism, especially on a compression ratio and ignition timing. The strong swirls were registered at all sharp edges on combustion chamber during compression stroke. These swirls had a strong influence on the combustion system operation.

Keywords*: internal combustion engines, spark ignition engines, combustion process, combustion process control, visualization of combustion process*

1. Introduction

The high-speed changes of physical-chemical phenomena in combustion processes and high temperature and pressure in the combustion chambers result in study of combustion process and combustible mixture preparation process being very difficult. These studies are much more complicated in the combustion chambers of piston engines, where the time of mixture preparation is very short, and the combustion process runs with a continuously varying pressure, density and temperature. The visualization methods, in the researches of combustible mixture preparation processes process are increasingly used. In these studies, the changes of medium density are utilized to record the events in the combustion chambers. For modelling processes in the visualisation engine researches are often utilized the devices, such as constant volume chamber, rapid compression machine (RCM), and visualization research engines. The design of modern combustion engines is very compact, making it difficult to install sensors and probes. In addition, the use of less complicated measurement devices allows elimination of certain factors influencing on the combustion process and thus they allows to specify how different parameters influence on the combustion process.

The development of visualization methods in engine researches in Poland dates back to the seventies of the twentieth century. The most successful attempts in this area can be regarded as the work of the Aircraft Engines Department of Heat Engineering Institute of Warsaw University of Technology [2, 3,15-19, 21], the Institute of Aviation Warsaw [4-13], and in recent years, Poznan University of Technology [20]. Visualization researches of combustion processes require the use of complex test stands and complex, high-precision research equipment. Of particular importance was the development of recording equipment for high-speed changing processes, laser equipment and computers with appropriate software, allowing controlling the research process and the data acquisition and processing. Along with access to the new equipment, the testing process and test methods were improved. Particularly important in the studies was to gain visual access to inside of combustion chamber using a digital camera, enabling rapid data registration over a relatively long duration. Previously used drum camera did not allow the long registration runs, due to the limited length of the film. Furthermore, the use of digital cameras enable a good coordination with the measurements of high-speed combustion pressure changes.

This paper presents the research results concerning the combustion mechanism in the combustion system with semi-open combustion chamber. The results show influence of the some parameters of combustion system on the burning mechanism, which determines the engine performance. It was stated that the combustion mechanism of the combustion system with semi-open combustion chamber is the main reason for the lack of linearity test results, which fundamentally differs this combustion system from the systems used in the standard piston spark ignition engines. Photographs of combustion, recorded with a digital camera let to look how the combustion process changed with different combustion system parameters. Furthermore, the process photographs in the combustion chamber allow capturing the vortices formation images at the edges of the combustion chamber and flows associated with the charge squeeze process during compression and expansion strokes.

2. Object of the study and test stand

The object of the study was the combustion system with semi-open combustion chamber, designed for spark ignition engines. The results of this system, however, can be also used for diesel engines. It is a system, which is dealing with a premixed combustion of combustible mixture, without considering of the mixture preparation process.

The test stand have been quite widely described in several publications [15-17]. The main difference in this case concerns the registration of combustion process with digital electronic camera and methods of acquisition and processing of research results. Therefore, the essential features of the test object and test stand are presented here only.

The standard combustion chamber in the cylinder head has been divided with partition into a pre-chamber and main combustion chamber. This division, however exists only when the piston is near TDC, when the partition face approaches the piston crown. For the remainder of the cycle (more than $\pm 10^0$ CABTDC) the chamber remains open. Ignition is initiated in the pre-chamber, using electric spark plug. When the pressure difference between the pre-chamber and main combustion chamber reaches a relevant value the jet stream of the burning mixture and radicals flows from the pre-chamber into the main combustion chamber. The speed of the stream flow through main combustion chamber should be greater than the combustion speed of free fuel mixture. The combustion will be performed with a higher speed and the combustion efficiency and the useful working field will increase. The main problem is to assure that the outflow of the mixture from the pre-chamber into the main combustion chamber occurs at the time when the piston is at TDC and the stream energy flowing through the orifice in the partition is sufficient to ensure that all jet stream quickly traverses across the combustion chamber, faster than the speed of combustion. The operating principle of combustion system is shown in Fig. 1.

The experiment was carried out using RCM, which allows the good optical access to the combustion chamber inside. In the combustion chamber heads of RCM the model, combustion chambers were installed. They modelled the ratio of pre-chamber volume to sum prechamber and main combustion chamber volumes and compression ratio.

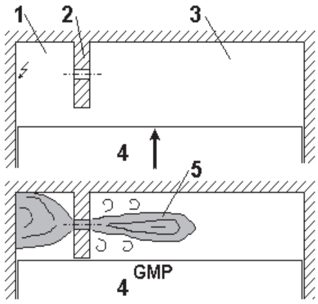

Fig. 1. Operating principle of the new combustion system: 1. Prechamber, 2. partition with orifice, 3. main combustion chamber, 4. piston, 5. stream of burned gases and radicals at the ignition the prechamber and the main combustion chamber are filled up with homogeneous, stoichiometric mixture and they are open, if piston is nearly TDC, the prechamber with burned gas is separated from the main combustion chamber and the burned gases begin to outflow from the prechamber to main combustion chamber

Fig. 2. Experimental test stand schematic: 1. Rapid compression machine, 2. Angle encoder, 3. Pressure transducer, 4. Spark plug, 5. Indiskope, 6. Electronic control module, 7. LED, 8. Computer PC, 9. Acquisition system chart, 10. Pressure amplifier, 11. Battery, 12. Ignition coil, 13. Interrupter, 14. Electronic control unit

Fig. 3. Test stand view

Figure 2 shows the diagram of the test standard Fig. 3 the test stand itself. The essential elements of the system are parallelepiped combustion chamber that provides a flat image of the combustion process in combustion chamber, easily and fast replaceable quartz glass (cleaning), and readily convertible model of the combustion chamber

Measuring system of the high-speed pressure measurements was made of by Kistler [15-17]. The digital camera for registration of combustion images Photram SA 1.1 was used. A major problem was to integrate the image acquisition system of combustion process with the high-pressure measurement system, and the ignition control system of the mixture.

3. The test results

Some examples of test results concerning the flame front displacement in the combustion system with semi-open combustion chamber are presented in the paper. Fig. 4 shows the combustion course registered by a digital camera in the model chamber with a prechamber relative volume of 28% (volume rate of the pre-chamber to the sum of the volumes of prechamber and main combustion chamber), the ignition advance angle of 50^0 CABTDC. The following photographs show the formation of a turbulent mixture in the combustion chamber at all sharp edges, and also outflow of mixture jet stream through the hole in the partition from pre-chamber. Outflow is due to the higher rapid pressure build up in the pre-chamber than in the main combustion chamber. Flame spread in the pre-chamber is laminar with the result that the combustion process in the pre-chamber is long. On the piston surface the boundary layer is formed. When the flame front in the prechamber approaches the orifice-hole in the partition a marked outflow of burning mixture and radicals is observed from prechamber, but in this case the piston is moving away from TDC, and a clearance is formed between partition and the piston crown. This flow conditions through this clearance are preferred because of the lower pressure drop. Therefore, the movement of the stream outflowing through the hole in the partition is reduced. The result is a "smoothing" of the flame front. It shows that a decisive influence on the combustion speed in the chamber has a stream flowing between the partition and the piston crown.

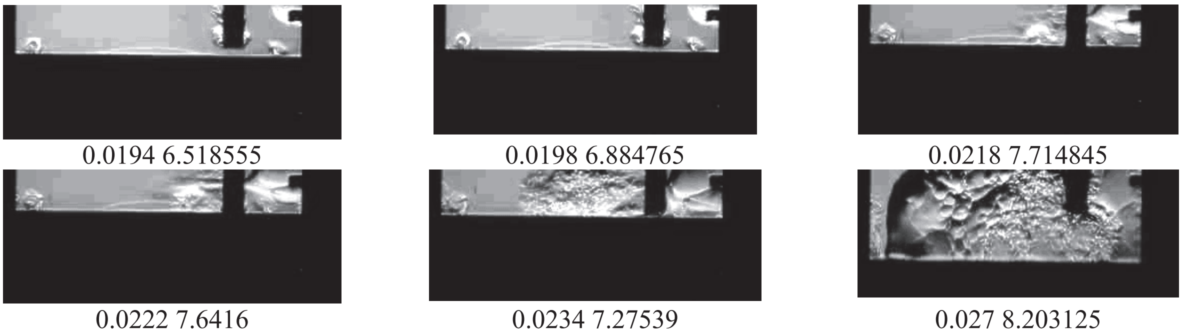

Fig. 4. Combustion course in combustion system with semi-open combustion chamber registered using digital Photram SA1.1 camera: V_P = 28 %; CR 6:1; IT=50^0 CA BTDC

This stream swirls on the edge of the partition. That direction of rotation cause a braking of the speed of the stream that outflowed through the hole in the partition and flows through the main combustion chamber space. The following photos show laminarization of advancing flame front. The indicator diagram shows the limits of combustion, frames from 0.0194 s to 0.027 s. They were selected from the research result collection concerning of RCM operating cycles. The indicator diagram (Fig. 5) shows that when the position TDC (time 0.0214 s) was reached, the measured pressure was much greater than the compression pressure, and yet there has been no outflow from the pre-chamber. When the outflow through the hole starts (time 0.0222 s) the piston moves away from TDC and the combustion pressure can no longer compensate the pressure drop due to expansion. Only after time 0.0234 s, combustion in the main combustion chamber is developed enough that exceeds drop caused by the expansion. Until 0.0266 s (combustion in main combustion chamber has lasted 4.4 ms) the pressure increases and after this time the expansion process is stronger and the pressure starts to drop. Therefore, the indicator diagram curve has two maxima; the maximum pressure is slightly greater than the compression pressure 0.72 MPa. In subsequent combustion process photographs showing vigorous mixing of the unburned and burned mixtures in the main combustion chamber and the prechamber, and the flow of combustion products from the main combustion chamber to the prechamber, since the pressure in the main combustion chamber reaches higher values than in the pre-chamber. For comparison, Fig. 6 shows the combustion course registered with photographic camera. It shows that, after the mixture ignition, flame front in pre-chamber spreads over the spherical surface, and is laminar, which determines the combustion time in the prechamber. When the flame front reaches the partition wall, the piston reaches the TDC, and follows the outflow of the burning mixture from the pre-chamber. However, soon appears a clearance between partition and piston crown, through which the stream begins to flow. This stream is experiencing swirl on the edge of the partition and brake the outflow through the orifice-hole in the partition. This reduces the displacement speed of the flame front through the main combustion chamber. The flame front becomes smooth, which indicates that the combustion is laminar and the flame front moves slowly to the opposite wall of the main combustion chamber.

The indicator diagram (Fig. 7) shows that the outflow stream from the pre-chamber into the main chamber was at the right time, because there is no pressure drop after passing the position of TDC, but the jet-stream energy was too low, since the pressure build-up, after passing through the TDC position of the piston is very slow. The maximum pressure value is small, but very far offset in relation to the position of TDC (0.83 MPa, 43.8^0 CABTDC), what in this case can be considered as a favorable factor, because it causes an increase by the work field.

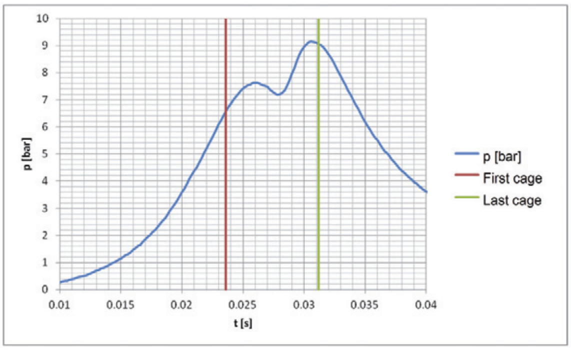

Fig. 5. Indicator diagram for combustion course presented in Fig. 4

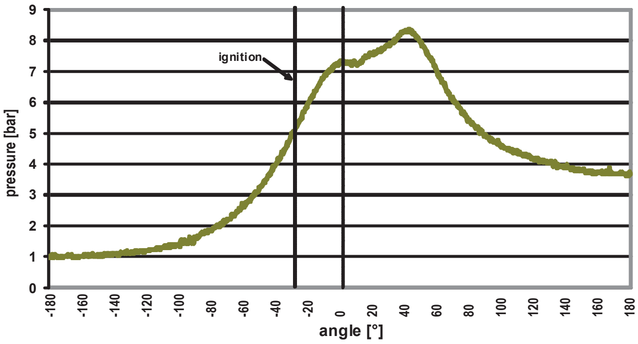

Fig. 7. Indicator diagram for combustion course presented in Fig. 6

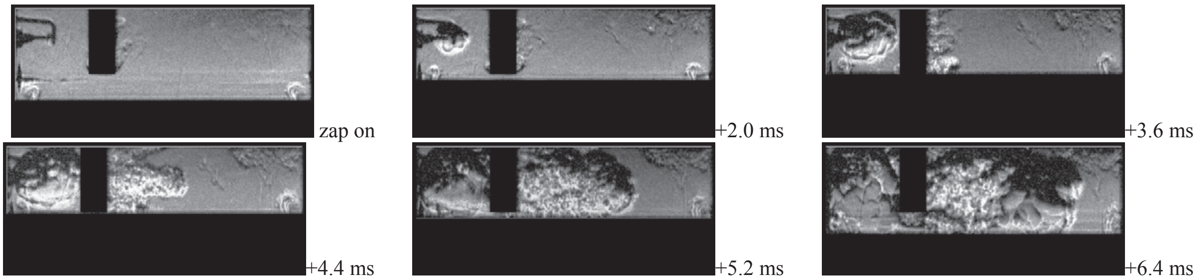

Fig. 6. Combustion course in combustion system with semi-open combustion chamber registered using photographic drum camera: V_p = 28%; CR 6:1; IT=30^0 CA BTDC

Figure 8 shows the combustion course in the combustion chamber with the least length of the main chamber in this study, while maintaining the relative volume of the prechamber 28%. Fig. 9 shows an indicator diagram obtained for this combustion process. The photographs clearly show the vortices formation on all sharp edges in the combustion chamber. Particularly intensive turbulence caused by the charge squeezing in combustion chamber (the left side of the drawing) from the space between the head and the piston crown. When the pressure difference between the prechamber and the main chamber is sufficiently large this causes the outflow from pre-chamber through orifice-hole in the partition (0.0264 s), a big swirl in a chamber occupies approximately 35% of the volume, and the stream outflowing from the prechamber has a clear difficulty, to break through the swirled space. It is than pressed against the upper surface of the head, but when it starts to slip over the back eddies; it is quickly sucked into the vortex and following vigorous mixing the burning and unburned mixture from the 5e stream. The following photos show an intense process of mixing in the main combustion chamber, the reverse flow between the chamber and the prechamber and to other open spaces, which appeared gradually as the piston move away from the TDC. Comparing photographs of combustion with high-speed pressure graph shows that at the time when the stream outflows from the pre-chamber (0.0264 s), the pressure is already quite high and is steadily growing.

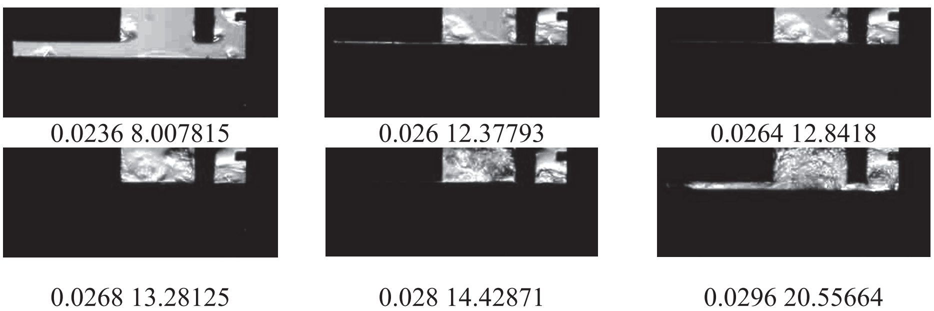

Fig. 8. Combustion course in combustion system with semi-open combustion chamber registered using digital Photram SA1.1 camera: V_p = 28%; CR 12:1; IT=60^0 CA BTDC

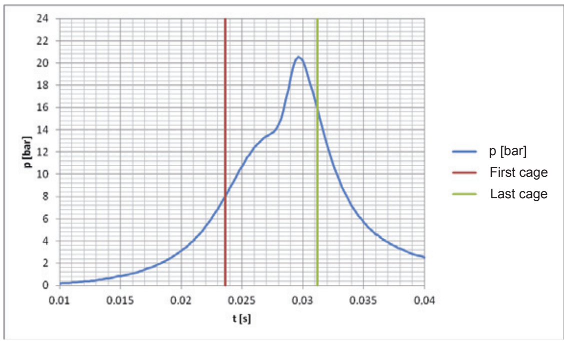

Fig. 9. Indicator diagram for combustion course presented in Fig. 8

Before the clearance between the partition and the piston crown opens, the combustion process in the entire volume of the combustion chamber takes place.

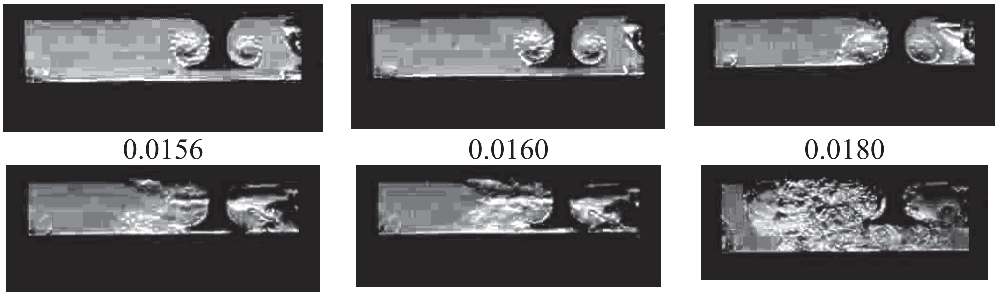

Fig. 10. Combustion course in combustion system with semi-open combustion chamber with specially shaped partition between prechamber and main combustion chamber registered using digital Photram SA1.1 camera: V_p = 08%; CR 6.5:1; IT=50^0 CA BTDC

Then the pressure in the main combustion chamber is higher than in the pre-chamber and begins a reverse outflow from the main combustion chamber to the prechamber.

Despite the increasing volume of the combustion chamber (expansion), increasing the pressure in the chamber reaches the maximum value of 2.06 MPa, over 1.2 ms after the opening of a clearance between the partition and the piston crown. As a result of the shortening of the combustion chamber, the high value of maximum pressure and a large field of useful work were obtained.

To assess the effect of swirl on the combustion process the combustion chamber with a specially shaped partition between prechamber and main combustion chamber was made. In the face of the partition special shapes with rounding were designed, whose task was to create a vortex at the inlet to the combustion chambers. The idea was to create a vortex to help to carry the burning mixture in the direction opposite to the wall where the ignition is initiated.

Figure 10 shows photographs of the subsequent combustion process in this combustion chamber. It shows that simultaneous formation of characteristic vortices at the edge of the pre-chamber and the main combustion chamber. When the combustion process in the pre-chamber is already sufficiently advanced, part of the fresh mixture from the pre-chamber is forced into the main combustion chamber, which disturbs the shape of the vortex (0.0180 seconds). However, the direction of rotation is not favourable to transferring the change coming out from the pre-chamber. Also the conditions in the prechamber are not favourable to carry out the charge of the burning mixture in the direction of orifice-hole. Swirl is so strong that it pushes the flame front to the upper surface of prechamber. Only when the piston passes the TDC and the clearance opens, the swirl changes the rotation direction and turbulence cooperate with swirl in placement of the jet stream outflowed through a hole in the partition However, the stream has too little energy to traverse the entire main combustion chamber. Furthermore, a clearance opening between the partition and the piston crown causes that the flow appears through clearance slot, at first from pre-chamber into main combustion chamber but when the pressure in the main combustion chamber is higher than in prechamber, in the opposite direction. Therefore, it turned out that the shape of the combustion chamber does not provide the expected results, however, it is an interesting picture of the vortices formation at the edge of the partition and it presents an impact on the combustion process.

4. Conclusions

1. The research aims to clarify the mechanism of combustion in the combustion system with semi-open combustion chamber for spark ignition engines.
2. Research visualization allows the observation of the combustion process, which is crucial for understanding the combustion mechanism, as the combustion parameter measurements are not sufficient in this respect.
3. In the study special attention has been devoted to the vortices formation at the edges of the combustion chambers, which greatly effect on the speed of the combustion process.
4. The length of the combustion chamber has an important influence on the combustion speed; if the length of the combustion chamber was reduced, the increase of combustion speed was observed, so the maximum pressure in the cycle and the useful work field increased.
5. The special shaped partition at the inlet to the combustion chamber allowed the formation of vortices in the prechamber and main combustion chamber; however, swirl generated did not help to intensify the combustion process (reducing of burning time).

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