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DESIGN OF THE RAPID COMPRESSION MACHINES FOR COMBUSTION RESEARCHES IN SPARK IGNITION ENGINES

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Abstract

The rapid compression machines (RCM) are extensive applied to combustion process researches and mixture process preparation research in the internal combustion engines (ICE). The principal advantage of these arrangements is easy optical access to the inside space of combustion chamber. This enables to observe the course of ignition process and the flame propagation process. There are some RCM designs, which they differ, first of all, the modelling method of piston movement into cylinder. The most known designs use the pneumatic and hydraulic drives. Their concern is that they enable the modelling compression stroke only but combustion is performed in constant volume combustion chamber. It was not relevant for the research of the new combustion system elaborated at Aircraft Engine Department of Warsaw University of Technology (AED). The RCM elaborated at AED has unique form it includes the crank mechanism, speedy operating electromagnetic clutch and flywheel. The applying of this design enables modelling the compression stroke and working stroke (two-stroke from engine cycle). It enables assessment of the system with semi-open combustion chamber what it will be impossible using other RCM designs. The different designs RCM used for combustion research at the research and development centres, on worldwide will be compared with the design of RCM developed at AED. The most known designs of the different RCM were described and the research result examples were given in this paper. The advantages and disadvantages of the different designs were discussed too in this paper.

Keywords: *SI engines, rapid compression machines, combustion chamber*

1. Introduction

The increasing requirements concerning fuel economy and exhaust emissions by internal combustion engines (ICE) cause that the researches of the physical and chemical processes are more complicated. It requires the better knowledge of the combustion mechanism. The ignition course and combustion efficiency have the most significant influence on the engine performance, especially their efficiency and emission. Despite that, the computational programs of engines are more and more sophisticated, which enables more and more exact reproduction of the combustion process parameters in the engines, but the exactness of these calculations is dependent from knowledge of the boundary conditions and different coefficients, which can be obtained as the experimental research results. But even the very exact calculation results must be verified experimentally. The physical and chemical processes in the engine combustion chambers are so complicated that their recognition in experimental way is continuously more important than the sophisticated theoretical considerations.

The researches using visualizations methods are very important in experimental works concerning combustion in the engines, because they enable the observation of the ignition and flame propagation processes inside combustion chamber. At present, there are the optical systems, with optical fiber, which enable a direct access to inside combustion chambers in the engines. But this access is very difficult because of compact design of the advanced engines (many valves, injectors, spark plugs, transducers etc.), located in the cylinder head. Therefore is very difficult to find the place to locate the additional optic system and to enable its management during testing. That is way, appear different solutions of the rapid compression machines (RCM) which enables an easy optical access to inside combustion chambers. So, it is possible to install the equipment to observe the phenomena during the mixture preparation, ignition and flame propagation. The RCM structure can be fit to each kind of the tests and the test equipment installed. Moreover, they can be adjusted to easy changes of the test equipment, and tested parts and units. The researches using RCM are one from many steps in research and development process of the ICE. In these tests the constant volume chambers, the experimental visualization engines and one-cylinder experimental engines are used. The final step in this research and development process is always the testing with apply real production engine.

A few designs of RCM are used at research and development centres, at worldwide. The different designs of RCM have been compared with the RCM design developed at Aircraft Engine Department of Warsaw University of Technology (AED) on this paper.

2. Designs of rapid compression machines

In worldwide research and development centres are a few design of the RCM. They have different structures. The basic difference of these designs relay on the applied drive of the working piston and numbers of the realized strokes in the engine cycle. The majority of this RCM design has the pneumatic and pneumatic-hydraulic drive, and performs only one stroke-compression stroke, but combustion lasts in constant volume combustion chamber. That is sufficient if the combustion process lasts and complete at TDC or close the TDC. In the real engines the combustion lasts few milliseconds, after pass of the TDC position. The consideration of the combustion time at changed volume is especially important for the researches of the combustion systems with semi open combustion chamber (with prechambers) in which the flame propagation process is essential dependent on piston position during stroke. When the piston is shifted, the flame propagation process is changed, what has essential influence on the engine performance. Therefore when at AED was developed the new combustion system with semi-open combustion chamber, which needed to develop the new original design of RCM, in which was applied the crankshaft too. Using this RCM can be observing the flame propagation process during expansion stroke. That was impossible if the researches using RCM pneumatically driven were performed.

2.1. Pneumatically driven rapid compression machine

The schematic of pneumatically driven RCM and their view are presented in Fig. 1 and Fig. 2, respectively. The design was developed as a first, earlier, project at AED. The test piston of this RCM is rigid joined with the auxiliary piston and damped element, which can move into oil chamber. In front part of the driven chamber and the rear part of damping oil chamber there is a blocking system, which keeps the piston assembly in the extreme (rear and front) positions.

The velocity of the piston assembly when the rear bolt of the blocking system is released, it depends on: the mixture pressure in a combustion chamber, the air pressure developed in the auxiliary piston, and the oil flow resistance in damped element. But suppress value of the piston assembly is depend on the oil flow velocity into the oil chamber, which can be controlled using the adjusting screws and the flow control value. The test piston stroke is constant and therefore to change the compression ratio it requires of the change of the cylinder length and cylinder head. In front wall of the cylinder head there is a visualization window, which enables the optical access to the interior of combustion chamber. In cylinder wall there is a long slot, which enables the optical access to combustion chamber from the rear part of piston, through transparent piston crown. In that case, the front wall of combustion chamber can be replaced by cylinder head with standard locations of the engine head elements in the real engine. The combustion chamber can be heated externally, what it enables obtaining that same initial temperature as during a real engine operation.

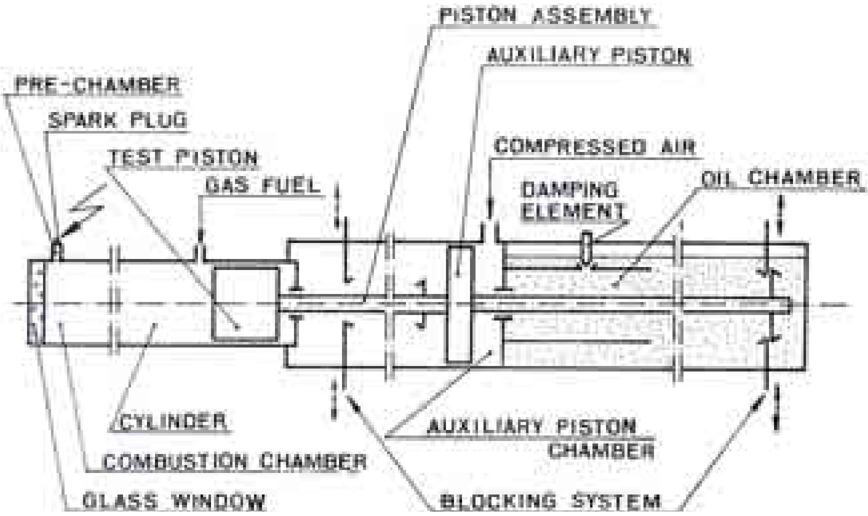

Fig. 1. Pneumatically driven RCM schema

Fig.2. View of pneumatically driven RCM

The orifices in the combustion chamber allow location of the different devices required in experiments: the spark plug, the injectors, the transducers and ending elements of feed and exhaust systems. The velocity of piston assembly can be varied first of all by changing the air pressure acted on the auxiliary piston. The area ratio of the test piston and auxiliary piston is 1 to 4. The reproduction a piston velocity in real engine can be obtained by varying the air pressure. If the damping effects are well selected, the velocity of test piston can be varied similarly as in operating engine. Before the test, the piston assembly is blocked in the extreme position that is in the lowest point of the test piston by blocking the damping element, and at the end of the test, in the top dead centre (TDC) by blocking of the auxiliary piston. The electronic control unit controls automatically the system operation, with the specially developed software. Below the test program for this RCM was presented.

Feeding the combustion chamber of the research mixture with predetermined properties (pressure, temperature, composition);Switching on the measurement equipment; Loading the high pressure air under auxiliary piston; Releasing of the blocking system rear element; Locking the bolt of damping element; When the diving piston get at frontal extreme place, the ignition is switched and registration equipment of measured results is switched on; After combustion completion all registration and measurement equipment is switched off but vacuum pump is put in motion to empty the combustion chamber from burning products.

If the exhaust gas are tested, then are conducted directly to the exhaust analyzer or they are collected in the bottles. The tested mixture feeding process can be automated, but this type of RCM is limited to execute only one working stroke so it is impossible to execute a few successive working cycles. The repeated start of RCM requires delocking of the driving piston and the piston displacement at rear extreme place. The trace (histories) of high-speed pressure in the combustion chamber in Fig. 3 is shown. On this diagram, it can be see the pressure variation during compression and combustion besides the combustion performs in constant volume chamber.

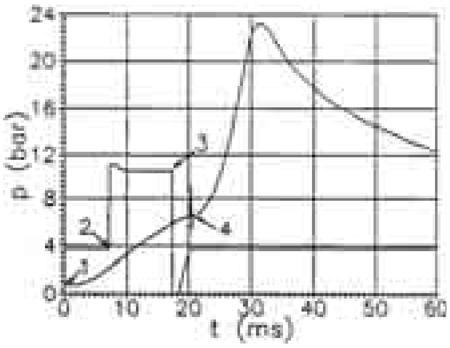

Fig. 3. Example of the high-speed pressure histories

This RCM was used at combustion research concerning PJC (Pulsed Jet Combustion) system developed by Professor A. K. Oppenheim, new combustion system with semi open combustion chamber and other combustion systems with dividing combustion chambers of SI engines. It was applied in research the ignition properties of hydrocarbon fuels additives and components used in compression ignition engines. The design of RCM applied by Griffiths and Kordylewski [3] in their research concerning of self-ignition delays of diesel fuels additives – DTBP (DiTetra Buthyl) is similar. The n-butane and methanol were research fuels; the first with very good self-ignition properties and second with very poor self-ignition properties. If the DTBP was introduced to the fuels, the self-ignition delay decreases to a few microseconds. The research results were utilized to develop the mathematical combustion model of fuels with DTBP additives. Fig. 4 shows the RCM schema which was applied in this research. The difference between the RCMs presented at Fig. 1 and Fig. 3 consists in the hydraulic damping chamber placement. In this design the damping chamber is placed in the middle of RCM, but the blocking system is all placed in this chamber. The working principle both of RCM is that same.

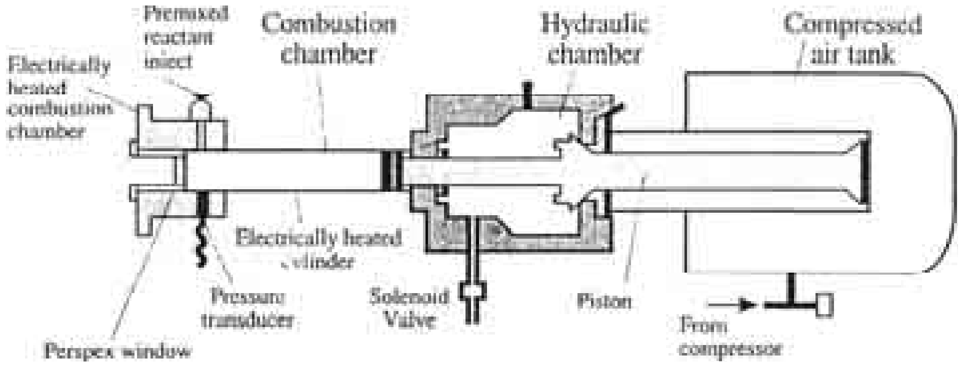

Fig. 4. RCM schematic with pneumatic drive, used by Griffiths and Kordylewski [3]

2.2. Pneumatically driven of cam system

The chapter before it was described the design of RCMs in which the driving piston was directly connected with compression piston and their displacement speed was depended on pressure acting under driving piston and damping of hydraulic block. So the air pressure or oil speed in dumping chamber must be controlled during compression piston stroke to obtain speed variation of the working piston similar to real engine.

Figure 5 presents the RCM designed and developed by Murase at Kyushu University (Japan). He used this RCM to research the courses of flame propagation in PJC system developed by A. K. Oppenheim. Similar design was realized in Poland at Institute of Aeronautics to research influence of fuel additives on ignition delay and burning rate. The small dimensions and the easiness of test run are most characteristic feature of this RCM. The speed of compression piston depends on the air pressure acting at the driving piston and a came shape. The compression stroke is limited by the cam lift. In either case, the change of RCM compression ratio requires a change of cam lift (that is a new cam).

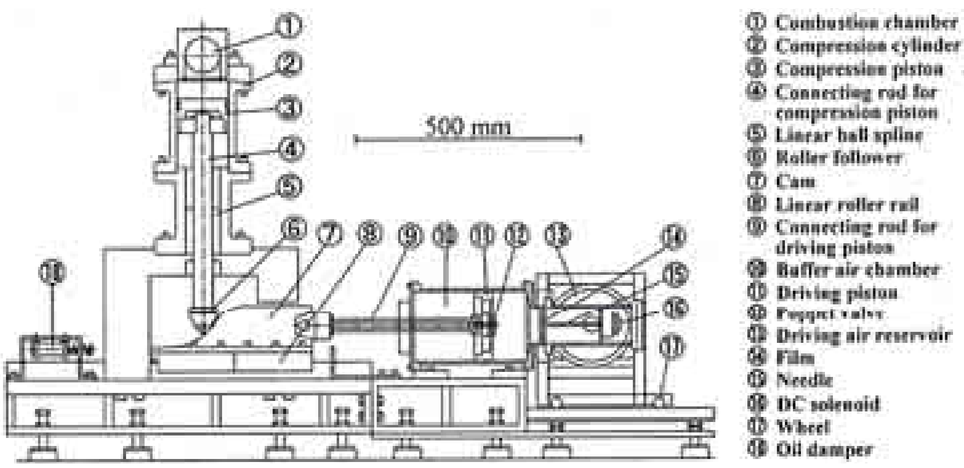

Fig. 5. Murase RCM used in research of pulsed jet combustion [6]

In this design, the cam, which reconstructs the piston movements, is pneumatically driven. The driving piston is directly connected with a cam and pushes the cam in parallel direction to your axis. On the cam surface, the roller moves and transfers the roller movement on by the connecting rod to the compression piston. The compression piston executes a movement in perpendicular direction to the driving piston. The velocity of compression piston displacement is depended on the cam velocity that is driving piston velocity. The combustion chamber can be heated outside, what enables to reproduce the conditions in real engine combustion chamber.

As an example in Fig. 6 shows the flame front displacement in combustion chamber obtained by Murase during research of PJC system for excess air coefficient $\lambda = 1.25$. In this experiment, the different hole diameters and localizations were applied. The research results were registered using photographic Schlieren method. On the combustion photographs can see, that the stream of burning mixture is very turbulized, what is aim of PJC system.

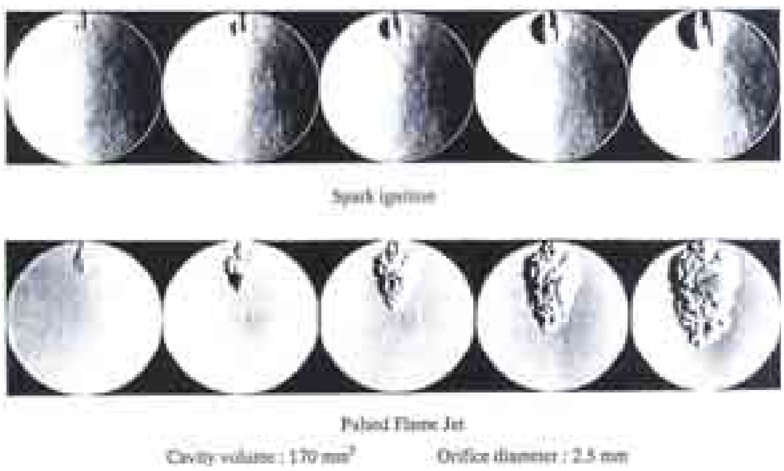

Fig. 6. Flame front propagation in the pulsed jet combustion [6]

Figure 7 shows next, similar to Murase RCM, design. However, in this design, the doubled cam is applied what enables a two stroke realization: the compression stroke and the expansion stroke (work stroke). So the combustion process is realized in varied volume of combustion chamber so as in the real piston combustion engine but not in constant volume of the combustion chamber so as in Murase design. Applying that design, the researches of different factors influence on the ignition and combustion in the HCCI process were conducted. The influence of: the air excess coefficient, the intake mixture temperature, the supercharging pressure and the different additives of heavy hydrocarbons to methane/air mixture, were tested. Simultaneously registered the burning photographies and the high speed pressure measurements were coupled one to another and presented in the most characteristic example of the following figures. Fig. 8 shows influence of initial mixture temperature on the HCCI combustion for the compression ratio, 22. If the initial mixture temperature was, 353 K only not numerous ignitions focuses appear at the end of compression and very small pressure growth was observed, although the combustion process begins earlier than at initial charge temperature 433 K. Fig. 9 shows an influence of compression ratio on HCCI combustion for a constant initial temperature of the charge, 433 K. The cross dots show the ignition places. It can see that ignition place is distanced from the cylinder wall, what is caused a decrease of the charge temperature close the wall. The compression ratio of 22 for that initial charge temperature was to low, and the fuel oxidation process goes too slow, and the heat release process was too slow. So for this example, the compression ratio should be greater or greater of the initial charge temperature.

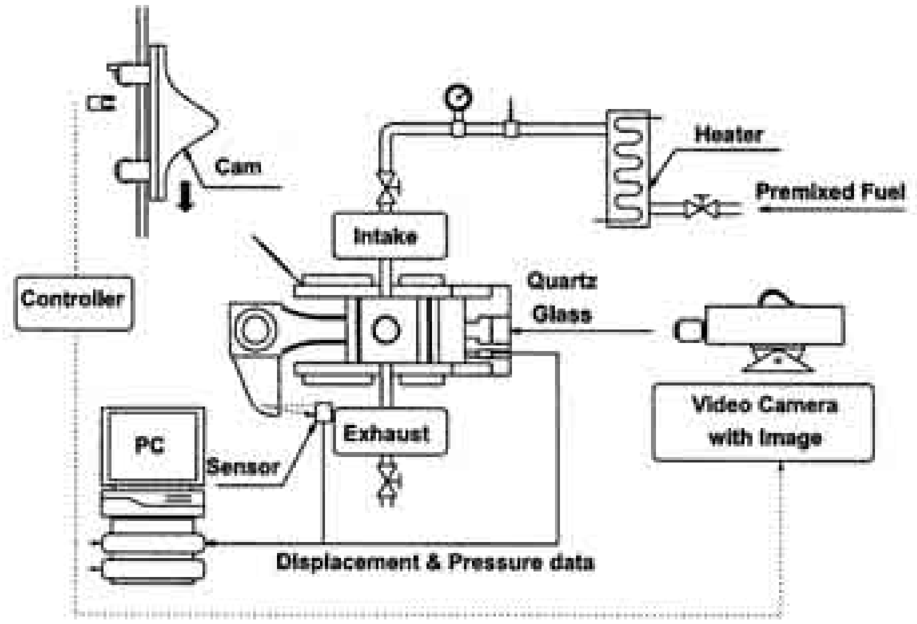

Fig. 7. Schematically presented RCM of pneumatically driven with doublet cam [1]

2.3 Pneumatic-hydraulic drive

Interesting and wide applied solution is RCM with pneumatic-hydraulic drive. The hydraulic equipment shapes the working piston velocity by variation of the pressure working mixture and moreover is applied to reverse piston movements. The piston can be locked in the any closed position. The pneumatic equipment is used during compression stroke, to compress the mixture into combustion chamber. Fig. 10 shows schematically the RCM, with pneumatic-hydraulic drive designed and manufactured at Massachusetts Institute of Technology (USA) [4]. The RCM contains two main oil chambers, separated by fast acting valve, and the locking system. The working piston is stiff joined with driving piston. The area of working piston is a few times smaller than area of driving piston. The outer oil chamber is the main oil reservoir, which operates at the relatively low pressure. The centre chamber is the speed control chamber and is designated for high pressures.

The oil from outer chamber to centre chamber is pushed with compressed air or nitrogen. The piston motion is realized with different air pressure (nitrogen) but a piston velocity is controlled by

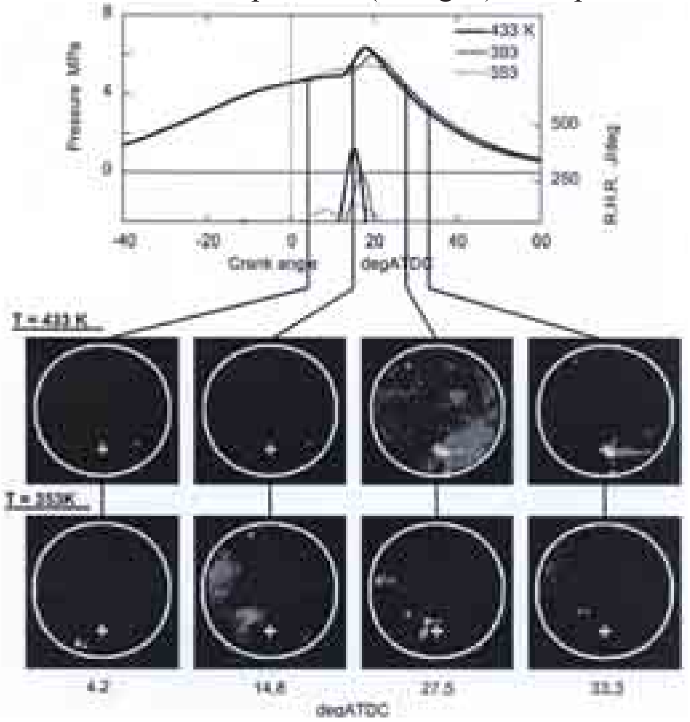

Fig. 8. Effect of intake charge temperature on HCCI combustion [1]

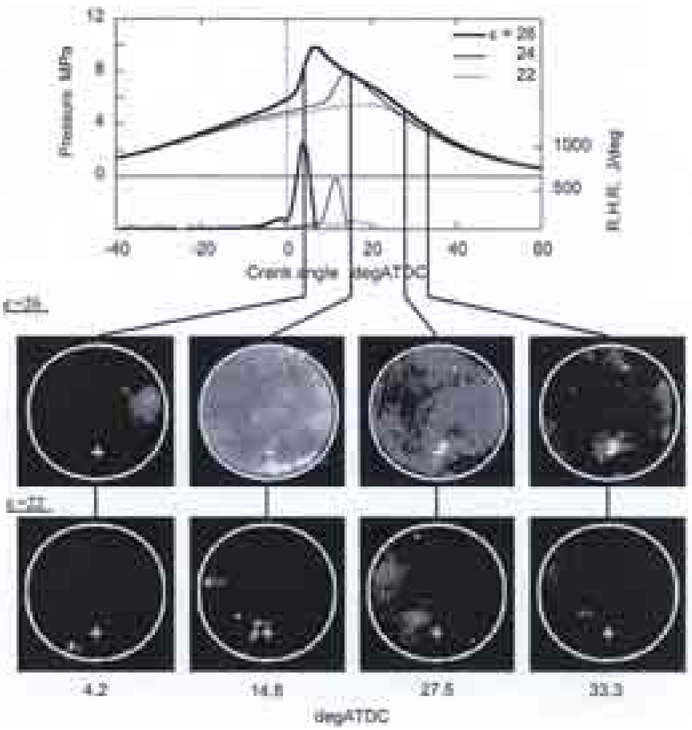

Fig. 9. Effect of compression ratio on HCCI combustion [1]

oil pressure in control chamber. The piston stroke and compression ratio can be adjusted to fit a desired value. Maximum piston stroke is 140 mm and compression ratio 19. The gas mixture can be compressed within 10 to 30 ms to pressure up to 7 MPa, what enables to model the determined engine speed. A combustion chamber can be heated externally, to reproduce the engine operation conditions. The RCM was applied by Tanaka et al [10] to research the ignition delay of fuel for

HCCI engines. Fig. 11 shows the combustion histories of the fuels with different octane number: 0 (n-heptane), 50, 75, 90 and 100 (iso-octane).

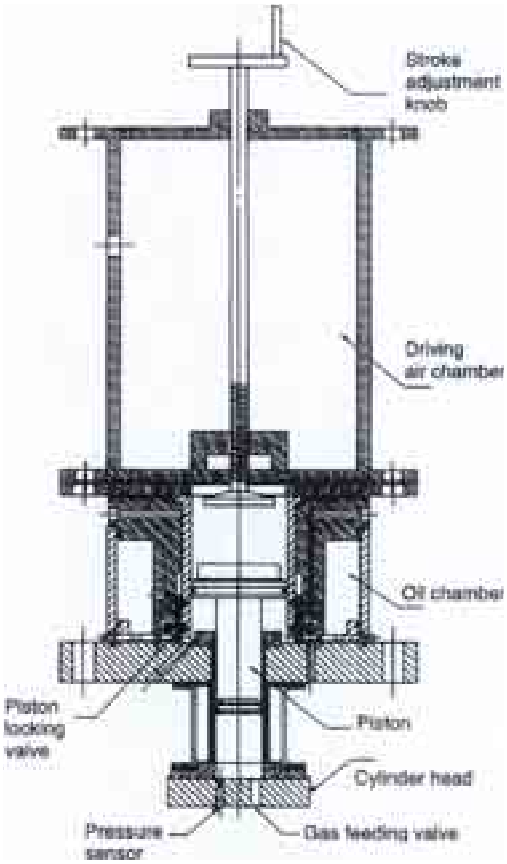

Fig. 10. Schematic of RCM from MIT [4]

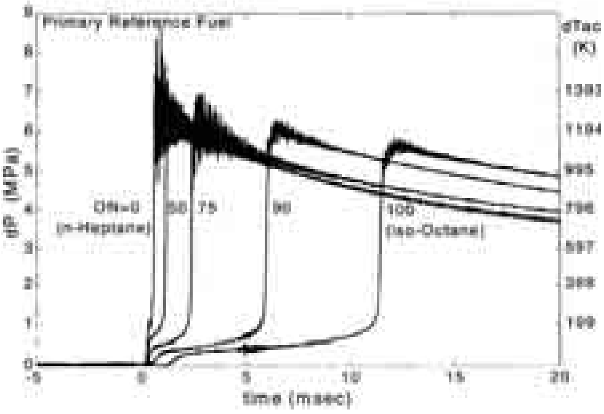

Fig. 11. Effect of octane number on ignition delay [4]

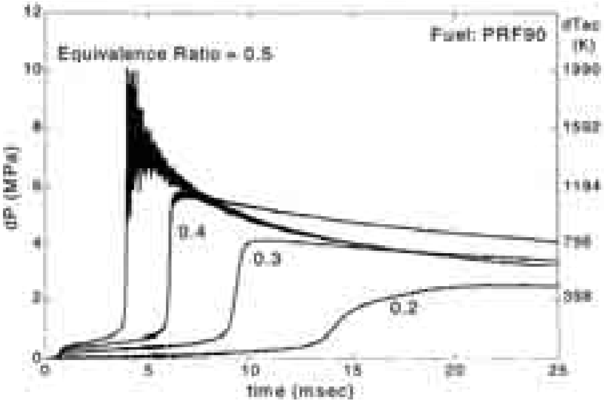

Fig. 12. Effect of equivalent ratio on ignition delay [4]

Mixtures of the reference fuels (n-heptane, iso-octane) were the fuels with in direct octane numbers (50, 75, 90). The equivalence ratio was fixed at 0.4, initial temperature and pressure were fixed at 318 K and 0.1 MPa, respectively, but compression ratio 16. It can be seen that ignition delay time increases as the octane number increases. The increment of ignition delay is particularly big if the octane number increases beyond 75. The ignition time delay for n-heptane was 0.672 ms but for iso-octane 11.32 ms (about 18 times longer). In another researches, conducted with this RCM, established that exists a great influence of air excess coefficient on the ignition delay; it increases when growths the air excess coefficient. It is vital importance to HCCI engines and compression ignition engines, which operate on very lean mixtures. Fig. 12 shows the courses of the ignition delay changes for different values of an equivalence ratio (reversal to air excess coefficient), for a reference fuel of the 90 octane number. It can be see that the ignition delay increases with decreases an equivalence ratio.

2.4. RCM with crankshaft

A RCM with crankshaft enables modelling the compression and expansion strokes in similar conditions as in the piston combustion engines. The researches of flame front displacement, conducted with combustion system with semi-open combustion chamber, shown that there is necessary to model the compression and expansion strokes, because its courses have a vital influence on the combustion process mechanism. This RCM was designed and manufactured at AED.

Figure 13 shows schematically the RCM with the crankshaft. The electric engine drives the RCM by pulley gear, and the flywheel with big mass and big inert torque. When the flywheel obtains a determined rotational speed, it is coupled with crankshaft of the RCM, using high speedy operated electromagnetic clutch. After coupling of the flywheel with crankshaft follows a small decrease of a rotational speed, but after a half rotation (1800 CA) the crankshaft enables a determined

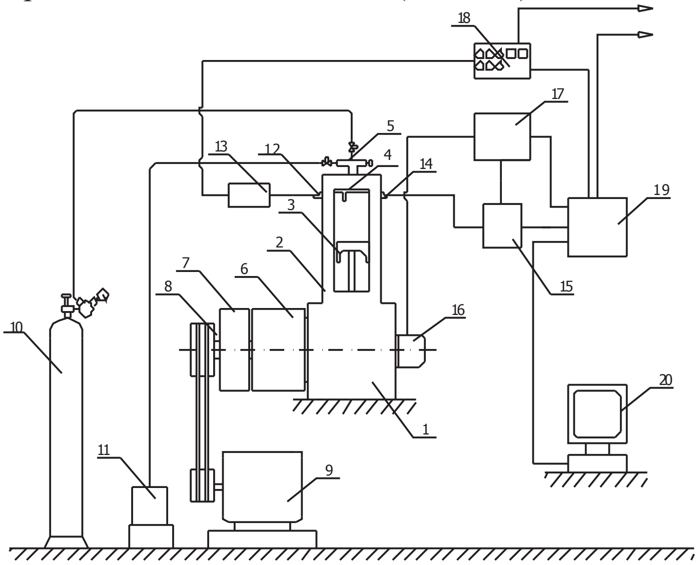

Fig. 13. Schematic of RCM test stand: 1 – crank mechanism, 2 – combustion chamber, 3 – .piston, 4 – insert model combustion chamber, 5 – refuelling and emptying system, 6 – electromagnetic clutch, 7 – flywheel, 8 – external belt transmission, 9 – electric motor, 10 – pressurized bottle, 11 – vacuum pump, 12 – spark plug, 13 – ignition apparatus, 14 – piezoelectric transducer, 15 – amplifier, 16 – crank encoder, 17 – indiskope 427, 18 – ECU of optical system, 19 – measurement card, 20 – PC

rotational speed. Fig. 14 shows the courses of the changes of rotational speed after the clutch push, when a piston is in TDC. After 1800 CA, the compression stroke begins and the crankshaft obtains a determined rotational speed. Fig. 15 shows the components of accelerations and their resultant value. How can see, the course of a piston acceleration is as in the real operating engine. The applying of that design solution of the RCM enables to identify to combustion process mechanism in the new combustion system with semi open combustion chamber. These processes can not be identified if the researches were conducted using the RCM with pneumatic drive, in which the compression stroke and the combustion in constant volumes only were realized.

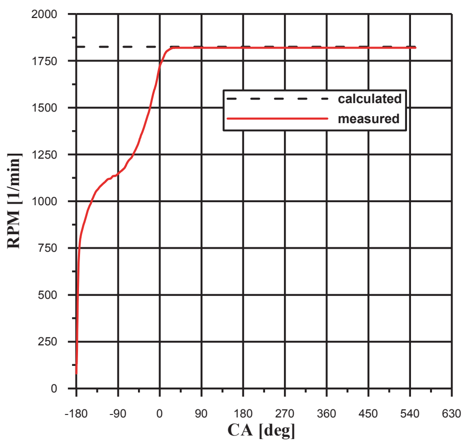

Fig. 14. Changes of rotation speed

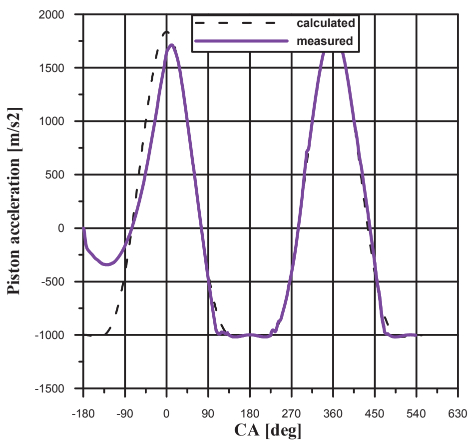

Fig. 15. Changes of piston acceleration

Figure 16 shows the combustion course, in the new combustion system with a small ignition advance angle, 100 CA. How can see the combustion in the prechamber is finished at the time when the piston pass the TDC position and is distant from this position. As a result, the clearance was formed between the piston crown and the partition, which has an area many time bigger than the hole area in the partition. So all outflow of the burning mixture and radicals, from prechamber to main combustion chamber, followed through the clearance and the combustion mechanism in this system was different from demanded, and the system performance was similar to the standard design.

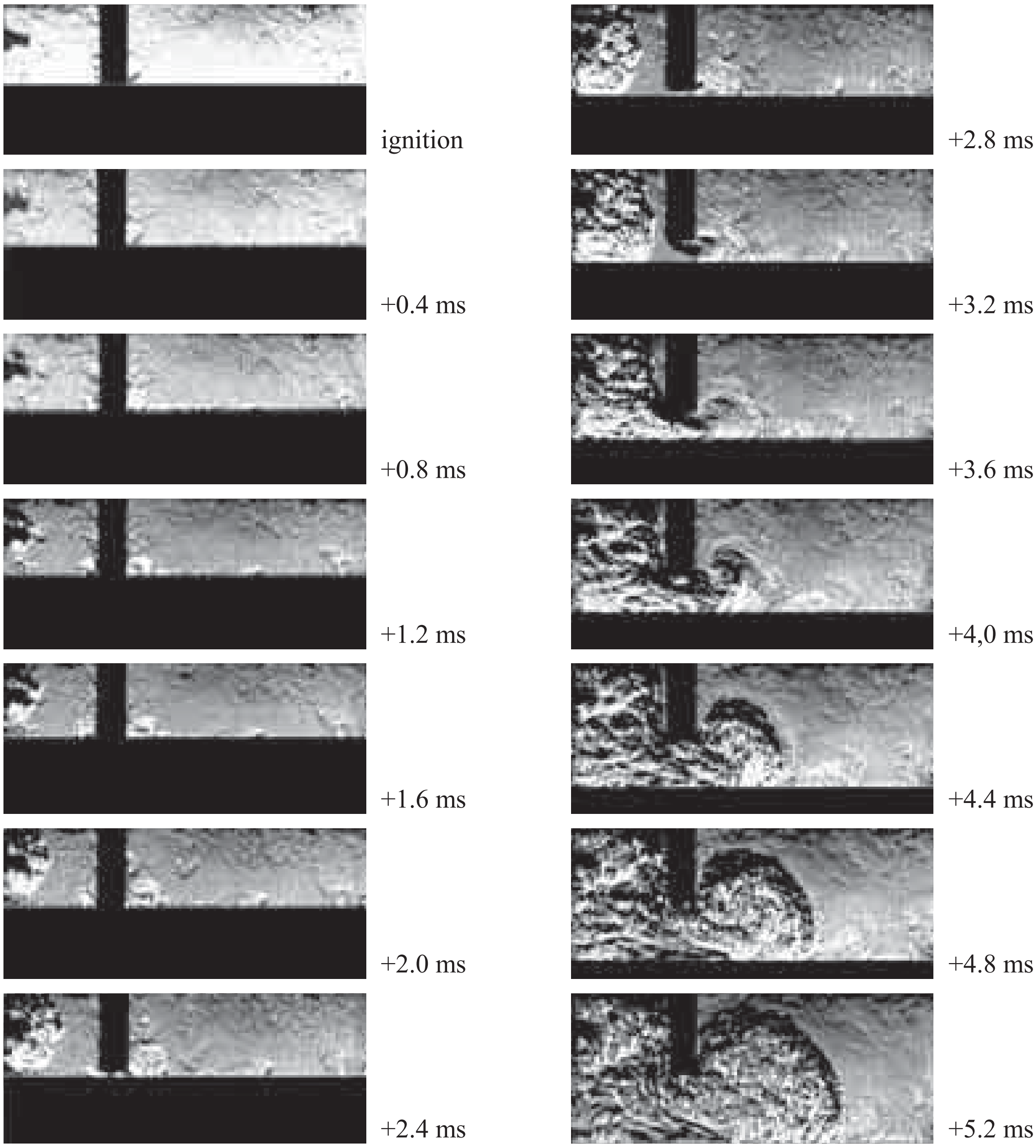

Fig. 16. Combustion process in a model combustion chamber during the tests using RCM: V_{kw} = 28%, d = 3 mm, ignition at the prechamber wall, φ_{wz} = 10°CA BTDC

Figure 17 shows the combustion course, in the new combustion system with big ignition advance angle, 450 CA. On the photographs can be see that the outflow of the burning mixture and the radicals, from the prechamber to the main combustion chamber, begins after 3.2 ms from ignition, before the piston achieves the TDC. This outflows stream undergoes the swirl at the partition edge. After about 3.6 ms, the clearance between the piston crown and the partition was closed and the stream from the prechamber to main combustion chamber begins to outflow through the hole in the partition. The swirl, which sets before, braked the stream, which outflowed through the hole in the partition, because the swirl speed vector is opposite to stream velocity vector. As a result, the velocity of stream, which outflowed through the hole, was smaller than in situation when the outflow begins at TDC and its energy is in sufficient to displace all main combustion chamber, before the outflow through the clearance undergoes. So, the elaboration of this original RCM design, with crankshaft, allows the identification of the combustion mechanism in the new combustion system. The researches shown a vital role the suitable values of ignition advance angle.

They had shown that the start of outflow from prechamber to main combustion chamber must undergo when the piston is at TDC position. This is difficulty in applying of the new combustion system in the real engine.

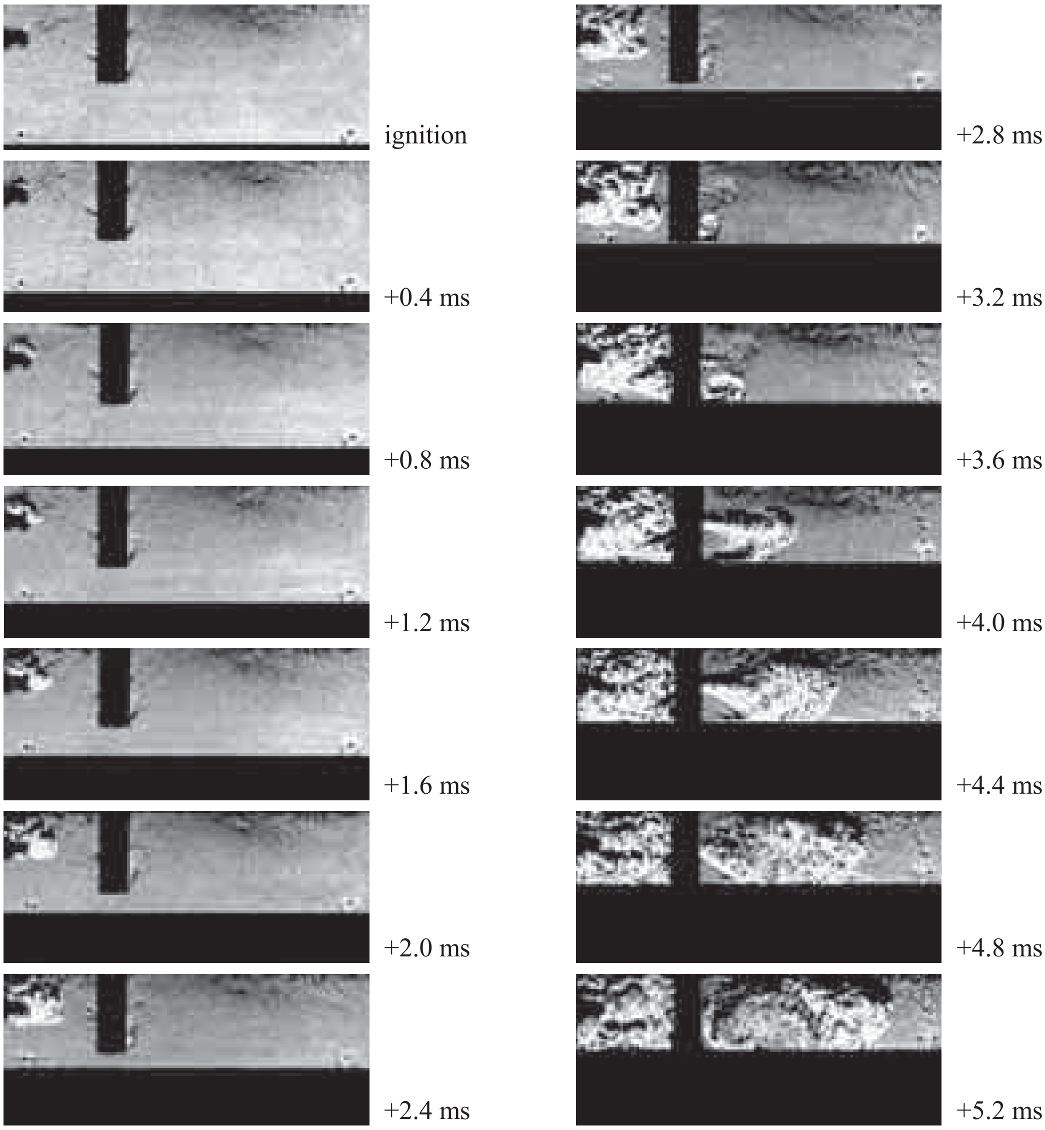

Fig. 17. Combustion process in a model combustion chamber during the tests using RCM: V_{kw} = 28%, d = 3 mm, ignition at the prechamber wall, φ_{wz} = 45°CA BTDC

3. Summary

The rapid compression machines (RCM) enable the realization of the difficult basic researches concerning the combustion process and mixture preparation process in piston internal combustion engines (ICE). The RCM are one from many experimental types of equipment but they are very important equipments because they allow modeling the physical and chemical processes in combustion chambers using visualization methods. The visualization methods are more and more frequently apply in the engine research. The design of the RCM should be fit to the experimental processes.

The most important differences in the RCM design concerns of the drive realization. In this point of view, the most popular are RCM with pneumatic and hydraulic-pneumatic drives. They have comparatively simple design and they are low cost in using and operation. In this paper are presented a few different designs of the RCM.

In Aircraft Engine Department of Warsaw University of Technology (AED) has designed and manufactured the original design of RCM with crankshaft, which allows the modelling two stroke from engine cycles; a compression and an expansion, while in the majority of RCM design the compression stroke only and combustion in constant combustion chamber are realized. The application of this RCM enables the testing of the combustion mechanism in the new combustion system for SI engines with semi open combustion chamber. This was impossible with other design RCM, because in this combustion chamber design the most important is recognizing of the flame front displacement during changed of the combustion chamber volume. The RCM with crankshaft is characterized by easy optical access to the combustion chamber interior in the axial cylinder direction and perpendicular to the cylinder axis. They are easy the changes of the tested parts too. The RCM can be externally heated, what allows a reproducing of initial working parameters of SI engines.

The researches with RCM using, are one kind, among many experimental devices, used during engine research and development. Among these devices are: the constant volume combustion chambers, the visualization engines, one cylinder research engines too. Each of these devices allows to do more simple the research processes for explain phenomena, by the emphasizing of the most important parameters and the eliminating of other secondary. So it can be easier to know the influence of different factors on the research phenomena and it is easier to influence on the engine operating parameters. In that method it can influence on the engine modernization directions.

The results of the modelling are very wide applied in the theoretical research, especially for mathematical models, which concerns the engine operation optimization. The knowledge of operating parameters allows to determine the different experimental coefficients, which are need to perfect the mathematical models.

However, it needs to remember that the final evaluation of the elaborated design of the engine must be made during real multi cylinder engine research.

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