ISSN: 1231-4005
e-ISSN: 2354-0133
DOI: 10.5604/12314005.1137620

FLAME FRONT PROPAGATION IN COMBUSTION SYSTEM WITH SEMI-OPEN COMBUSTION CHAMBER WITH DIFFERENT COMPRESSION RATIO

Tomasz Leżański, Janusz Sęczyk, Piotr Wolański

Institute of Heat Enginering, Warsaw University of Technology
Nowowejska Street 21/25 Warszawa, Poland
tel.:+48 22 2345266
e-mail: leżański@itc.pw.edu.pl

Abstract

Researches of the combustion system with semi-open combustion chamber for spark ignition engines. This system was elaborated in Aircraft Engine Department of Heat Engineering Institute of Warsaw University of Technology. The researches concern the determination of influence CR on a flame front propagation into combustion chamber when CR and ignition advance are varied. The model combustion chamber make up with the constant volumes ratio of the prechamber volume to the prechamber plus main combustion chamber volumes, of 28%, but the CR were varied: 6:1, 8:1, 10:1 and 12:1, by changing of combustion chamber length. The researches were performed using rapid compression machine (RCM). The combustion sequences were recorded using high-speed digital camera with speed of 5000 frames per second. Simultaneously with combustion sequences recording, the high-speed pressure measurements were performed. The results of the visualization researches, with the pressure measurement results are presented in the paper. The research results show that the growth of compression ratio caused an improvement of combustion system performances; an increase of maximum cycle pressure and useful work field. The improvement of the performances is caused mainly by shortening of the combustion chamber length and approaching of supposed combustion course.

Keywords*: internal combustion engines, spark ignition, combustion processes, new combustion systems, combustion process visualisation*

1. Introduction

The ideal cycle analysis showed that indicated fuel conversion efficiency increased continuously with the compression ratio (CR). However, other processes which influence on engine performance and efficiency vary with changes CR, for example: combustion rate and stability, heat transfer, and friction. Over the load and speed range, the relative impact that these processes have on power and efficiency varies also. Moreover, the ability to increase of the CR is limited by the octane quality of fuels and knock. In the combustion system with semi-open combustion chamber the growth of CR is additionally limited by combustion mechanism, because this combustion mechanism in the combustion system with semi-open combustion chamber is strongly depended on the ignition advance angle and a stream (jet) range outflowing from prechamber to main combustion chamber through the orifice hole in the partition. Other combustion system parameters have smaller influence on combustion system performances. Therefore, it was suitable to recognize what is mechanism of flame front propagation in the combustion system with semi-open combustion chamber for different CR.

Researches of the combustion system with semi-open combustion chamber for spark ignition engines. This system was elaborated in Aircraft Engine Department of Heat Engineering Institute of Warsaw University of Technology. The researches concern the determination of influence CR on a flame front propagation into combustion chamber when CR and ignition advance are varied.

So, the test stand, measurement equipment and model combustion chambers have been prepared. The model combustion chamber make up with the constant volumes ratio of the prechamber volume to the prechamber plus main combustion chamber volumes, of 28%, but the CR were varied: 6:1, 8:1, 10:1 and 12:1, by changing of combustion chamber length. Therefore, the CR was increased; simultaneously the combustion chamber volume was decreased. The researches were performed using rapid compression machine (RCM). The combustion sequences were recorded using high-speed digital camera with speed of 5000 frames per second. Simultaneously with combustion sequences recording, the high-speed pressure measurements were performed. Apply these results the combustion course with pressure course curve were compared. If the length of combustion chamber was smaller, the burning time in combustion chamber was shorter but pressure results increased. The strong swirls were observed on the edges of combustion chamber. They have apparently influence on the combustion mechanism, because they brake the propagation of stream outflowing to main combustion chamber from the orifice hole in the partition.

The results of the visualization researches, with the pressure measurement results are presented in the paper. This results concern combustion system with semi-open combustion chamber for spark ignition engines, but they show how the flame front can propagate in another engines, too.

2. Experimental apparatus and procedure

2.1. Test stand

Figures 1 and 2 show the test stand schematic and the test stand view, respectively. Application of the RCM allows obtaining of high-speed combustion photographs at very good quality, in the plain goes over the longitudinal axis of the combustion chamber. Moreover, it does independent of research results from disturbance caused by cyclic induction and exhaust processes.

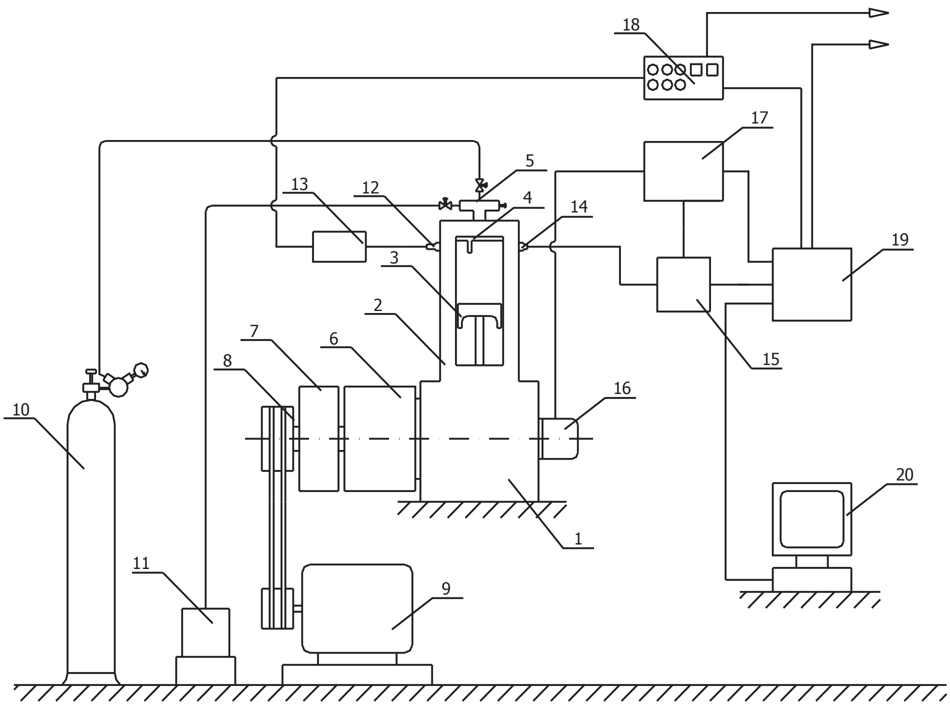


Fig. 1. Schematic of RCM test stand. 1. Crank mechanism, 2. Combustion chamber, 3. Piston, 4. Insert model combustion chamber, 5. Refuelling and emptying system, 6. Electromagnetic clutch, 7. Flywheel, 8. External belt transmission, 9. Electric motor, 10. Pressurized bottle, 11. Vacuum pump, 12. Spark 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

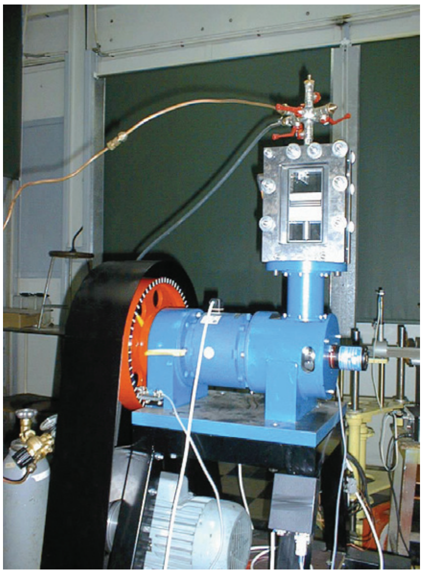


Fig. 2. View of test stand

Crankshaft of RCM was driven with electric motor; power 3 kW, by an external belt transmission, which allows obtaining required RCM speed in short time after switch on of the electromagnetic clutch. At the beginning, a flywheel powered by the electric motor reached required speed to conduct the test, and then electromagnetic clutch was connected with RCM crankshaft. The crankshaft of RCM due to big power of electric motor and big inertia moment of flywheel, very soon, after about 90^{o}CA, gained required speed – 1800 RPM. Only compression stroke and power stroke were realized with RCM. Pressurized bottle was used to feel up the combustion chamber before testing but the vacuum pump was using for emptying the chamber after test. The homogeneous, stoichiometric the test mixture of air /natural gas (contained 96% of methane) was used. The test mixture was prepared in pressurized bottle for all tests, before start of research to avoid the discrepancies of a composition for subsequent tests.

2.2. Rapid Compression Machine (RCM)

The RCM includes crankshaft, connecting rod, sliding rod, piston and combustion chamber. Cross section of the piston is rectangular, but combustion chamber is parallelepiped. In combustion chamber, a special shaped inserts, modelled combustion chamber of real engine, were fixed. The quartz windows in a front and back walls were mounted, to assure optical access into combustion chamber. Volume of combustion chamber, in specification is done summary volume of prechamber and main combustion chamber. In successive tests, the ratio volume of prechamber to main combustion chamber was varied, but summary volume was constant. The volume of prechamber is presented in percent with respect to summary volume. In head of combustion chamber, the spark plug and valve for refilling and emptying combustion chamber were installed. Elimination of train valves mechanism from RCM design enables the excellent optical access into combustion chamber.

2.3. Combustion process visualization

Figure 3 shows optical system applied in the research. This system include plain and concave mirrors, lenses, optical knife, source of light and electronic digital camera, Photram SA 1.1. In optical system parallel luminous flux, which illuminate the research volume, was shaped. The light source was the light emitting laser diode.

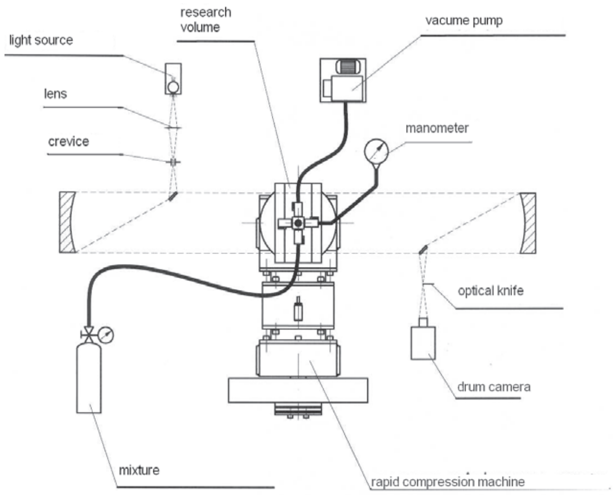


Fig. 3. Schematic of the optical system

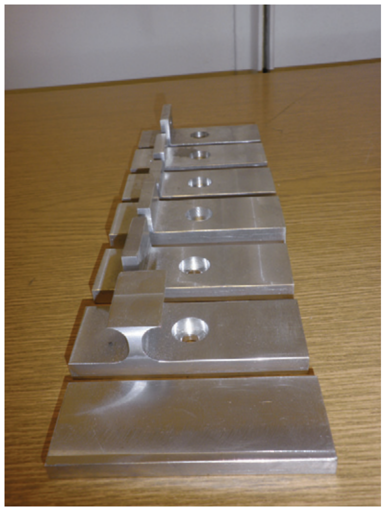


Fig. 4. View of combustion chamber models before testing

The images were registered in big computer memory with frequency – 5000 frames per second, exposition time 50μs.

3. Research results

The research objects were the model combustion chambers, in which the constant ratio of a prechamber volume to amount of prechamber and main combustion chamber volumes were set: 28 percent. Therefore, the prechamber volume is expressed in percents. The compression ratio (CR) was varied from 6:1, through 8:1 and 10:1 to 12:1. The height of combustion chamber was set, but the length of main combustion chamber was varied. Fig. 4 presents the view of the model combustion chamber, which were fixed in cylinder head of rapid compression machine (RCM). During testing of the model combustion chambers, the ignition timing (ignition advanced angle) was changed from 20^0 CABTDC to 70^0 CABTDC, to determine the intensive stream outflow of burning mixture and radicals, from prechamber to main combustion chamber, through the orifice hole in partition, when piston is at TDC. The mixture ignition was initiated in the prechamber. The orifice hole diameter was 3 mm. The orifice diameter, the prechamber volume, the ignition place and the ignition timing are the most important parameters of combustion system with semi-open combustion chamber. They decide about the combustion mechanism in this system and the performances of the system.

3.2. Flame front propagation in combustion chamber

During the tests, the photographs of the combustion courses were performed, using an electronic high-speed camera and the high-speed pressure were measures. The combustion courses for different CR will be presented on the selected examples. They make possible to estimate how the CR influences on the combustion process, maximum cycle pressure, and other system performances. The presented photographs and pressure curves concern the results which were obtained for the best of ignition timing for determined of CR, when the maximum pressures were achieved. It is necessary to stress, that in the combustion system with semi-open combustion chamber it is required to obtain the beginning of the stream outflow of burning mixture and radicals from prechamber to main combustion chamber when the piston is at TDC, and stream energy will be enough to propagate all main combustion chamber before the clearance between piston crown and partition appears. This is very difficult to achieve, especially in automotive engines in which the loads and speeds are very frequently varied.

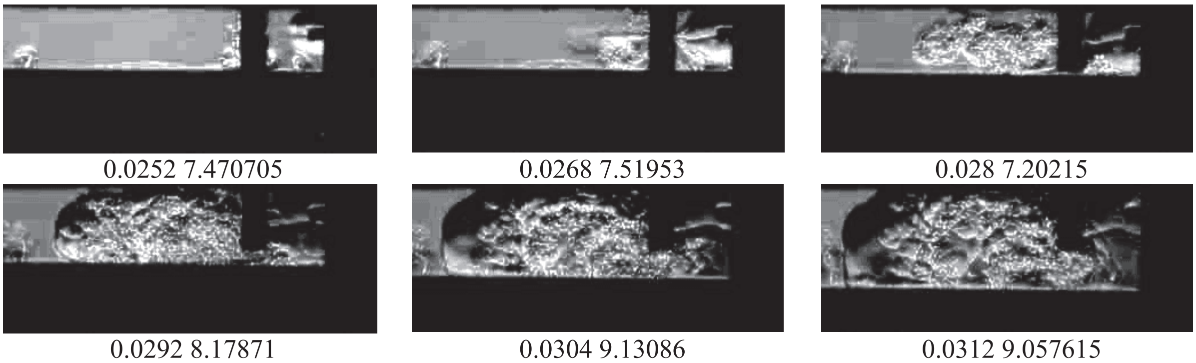


Fig. 5. Combustion process development in combustion chamber model: Vp=28%, CR 6:1; IT=30^0 CABTDC

Figure 5 shows the course of combustion in the combustion chamber with CR 6:1 and ignition timing 30^0 CABTDC. The outflow from prechamber to main combustion chamber starts, when the piston passed the TDC (0.0272 s), in spite of the stream outflowed from orifice hole in partition quickly propagated across the main combustion chamber. Initially, combustion process was too slow, to equalize a pressure decrease caused by expansion process. This can see in high–speed pressure curve as a decrease of pressure before TDC. After the time about 0.8 ms from the prechamber outflow the pressure begins to increase. The maximum pressure value was little bigger than the compression pressure, that is 0.913 MPa and 0.747 MPa, but it was gone away TDC, and therefore the work field was big for this cycle.

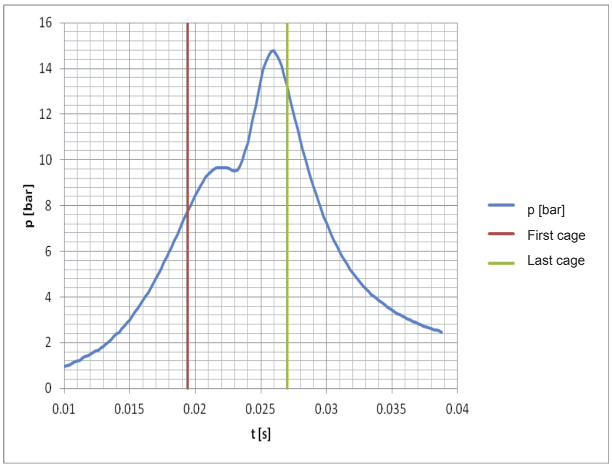


Fig. 6. High-speed waveforms of pressure in combustion chamber as a function of burning time: CR: 6:1, IT=30^0 CABTDC

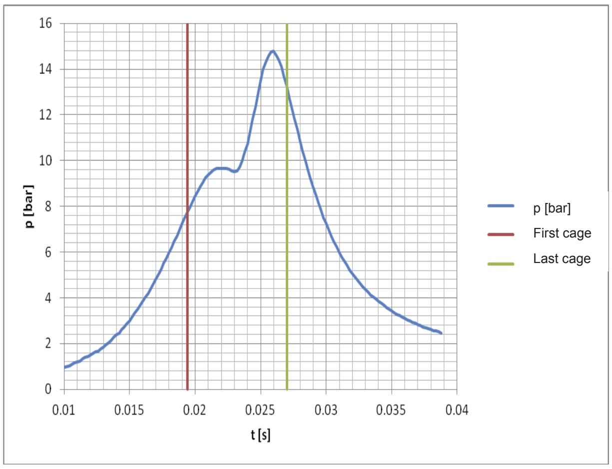
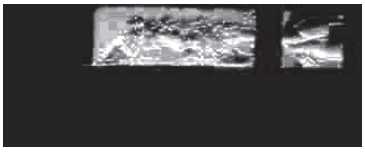
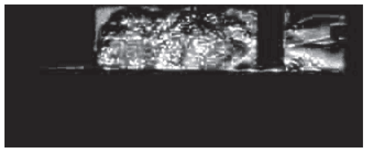


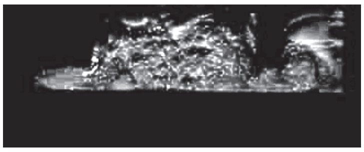
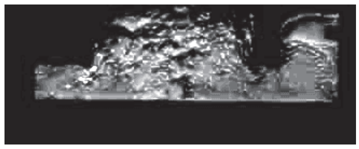
Fig. 8. High-speed waveforms of pressure in combustion chamber as a function of burning time: CR= 8:1; IT= 40^0 BTDC

Figure 6 compares the high-speed pressure curves for ignition timing of 30^0 CABTDC and for compression and expansion without combustion. Fig. 7 shows the course of combustion in the combustion chamber with CR 8:1, and ignition timing 40^0 CABTDC. The outflow from prechamber to main combustion chamber starts when the piston was at TDC (0.0222 s). This stream flame front quickly propagate across the main combustion chamber, and after the time of 1.6 ms it achieves opposite wall of main combustion chamber, before the clearance between the piston crown and partition appears.

When the clearance was opened, the riversides flow from main combustion chamber to prechamber began, because the pressure in main combustion chamber is higher than in prechamber. Moreover, the intensive mixing of the charge in all space of combustion chamber and continuous pressure growth are observed. The high pressure maximum, of 1.475 MPa is obtained in the time about 3.6 ms from the moment of outflow from prechamber. In the movies photographs

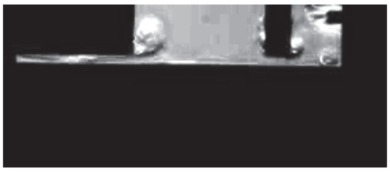
0.0222 9.66797 0.023 9.521485 0.0238 10.35157

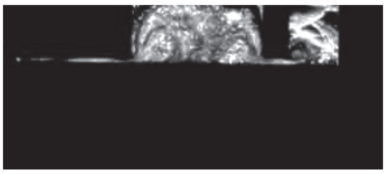
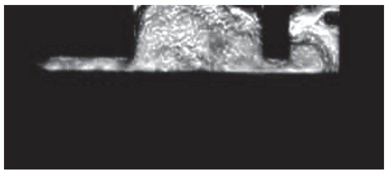
0.025 13.50098 0.0258 14.7461 0.0266 14.08692

Fig. 7. Combustion process development in combustion chamber model: Vp=28%, CR= 8:1; IT=40^0 CABTDC

the intensive flows, highly tubulised charge between prechamber and main combustion chamber and numerous streams outflowed from different crevices of combustion chamber can see. Fig. 8 presents the high-speed pressure curves for the ignition timing 20^0, 40^0 and 70^0 CABTDC. The reason from these curves it can be estimate influence of ignition timing on the maximum pressure value and the useful work filed. These values are similar for the ignition timing 40^0 and 70^0 CABTDC, but for higher ignition advance angle the compression filled is higher, because a burning mixture is compressed instead of the fresh mixture. In the photographs of combustion course it can be seen, that decrease of the main length of combustion chamber was profitable for the combustion mechanism realization, because the high speed useful field and high maximum pressure cycle were obtained.



0.0230 9.5459 0.0246 11.71875 0.0254 12.62207

0.0258 13.20801 0.027 18.13965 0.0278 21.41114

Fig. 9. Combustion process development in combustion chamber model: Vp=28%, CR= 10:1; IT=40^0 CABTDC

Figure 9 presents the course of combustion chamber with CR 10:1 and ignition timing 40^0 CABTDC. The length of main combustion chamber is smaller than former and is 9.4 mm. In the photographs during compression stroke very strong swirls formation can be seen at all sharp edges of combustion chamber and especially on the left side of combustion chamber. Above the piston crown a surface layer is created. When the piston comes to the TDC the swirls are stronger and stronger. The outflow from prechamber to main combustion chamber begins when the piston was at TDC (0.025 s), but the vortex was so strong, that the stream outflowed from orifice hole was pushed up to higher surface of combustion chamber. This stream not till when was at the wave crest it was drawn in the middle of the vortex. In effect, the speed of mixing increased and the stream quickly achieves the opposite wall of main combustion chamber. The stream achieved the opposite wall, before the clearance between piston crown and partition was opened. When the clearance appear the burn up process of the charge and intensive mixing begins. The flows between prechamber and main combustion chamber, and jet stream from different crevices were profitable for this process.

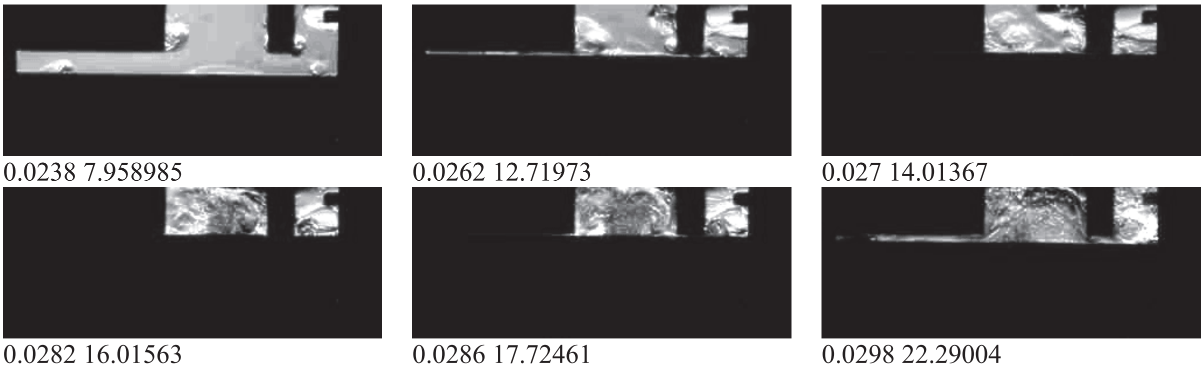


Fig. 10. Combustion process development in combustion chamber model: Vp=28%, CR=12:1; IT=50⁰ CABTDC

Figure 10 shows the course of combustion in combustion chamber with CR 12:1 and ignition timing 50^0 CABTDC. The length of combustion chamber was 25 mm, whereas the longest of main combustion chamber had 56 mm. the course of combustion was very similarly as for CR 10:1. It can be seen that appeared very strong swirl during compression stroke especially on the left side of main combustion chamber. The outflow from prechamber to main combustion chamber begins before TDC of the piston (0.0262 s). However, directly after closing of the clearance between piston crown and partition, the stream achieves the opposite wall of main combustion chamber (0.027 s). Owing to the intensive mixing of burned and not burned mixtures in combustion chamber is initiated. At the time 0.0298 s, the maximum cycle pressure – 2.23 MPa was achieved.

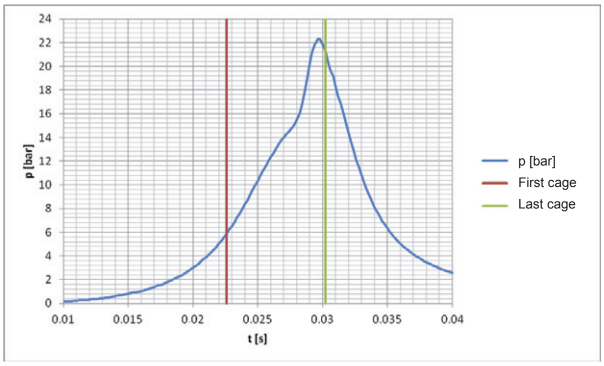


Fig. 11. High-speed waveforms of pressure in combustion chamber as a function of burning time: CR= 12:1; IT=50^0 CABTDC

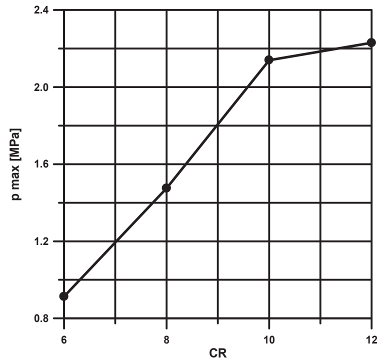


Fig. 12. Influence of compression ratio (CR) on the cycle maximum pressure

Figure 11 shows the history of high-speed pressure for the ignition timing of 50^0 CABTDC and for compression and expansion. Fig. 12 shows dependence between maximum pressure value and compression ratio, for the most profitable values of ignition timing for each CR. The length of the main combustion chamber was varied but their height was constant, when changing CR. The growth of CR causes substantial increase of maximum cycle pressure.

4. Conclusions

1. The principal problem of operation combustion system with semi-open combustion chamber consists in to assure that jet-stream outflow from prechamber to main combustion chamber begins when the piston is at TDC, and the jet-stream will have a sufficient energy to displace quickly all combustion chamber, before the clearance between piston crown and partition appears.
2. The combustion system with semi-open combustion chamber enables the improvement of engine performances: engine efficiency, repeatability of ignition, reliability improvement, exhaust emissions if the combustion systems parameters will be well matched.

3. The research results show that the growth of compression ratio caused an improvement of combustion system performances; an increase of maximum cycle pressure and useful work field.
4. The improvement of the performances is caused mainly by shortening of the combustion chamber length and approaching of supposed combustion course.
5. The increment of maximum cycle pressure values was bigger when compression ratio growths from smaller compression ratios; growth of compression ratio from 6:1 to 10:1 causes growth of maximum pressure about 2.3 time, but from 10:1 to 12:1 only 4.2 percent.
6. Visualisation of combustion process showed that in the sharp edges of combustion chamber the strong swirls are formed which had a big influence on combustion course.

References

[1] Glinka, W., Leżański, T., Wolański, P., *Badania procesu spalania w maszynie pojedynczego sprężu z wykorzystaniem szybkiej fotografii smugowej*, Journal of KONES Powertrain and Transport, Vol. 14, No. 4, 2007.

[2] Jankowska-Siemińska, B., Jankowski, A., Slezak, M., *Analysis end research of piston working condition of combustion engine in high thermal load conditions*, Journal of KONES Powertrain and Transport, Vol. 14, No. 3, pp. 233-243, 2007.

[3] Jankowski, A., Czerwinski, J., *Memorandum of Prof. A.K. Oppenheim and an ex ample of aplication of the Oppenheim Correlation (OPC) for the heat losses during the combustion in IC engines*, Journal of KONES Powertrain and Transport, Vol. 17, No. 2, pp. 181-194, 2010.

[4] Jankowski, A., *Heat transfer in combustion chamber of piston engines*, Journal of KONES Powertrain and Transport, Vol. 17, No. 1, pp. 187-197, 2010.

[5] Jankowski, A., *Laser research of fuel atomization and combustion process in the aspect of exhaust gases emission*, Journal of KONES Powertrain and Transport, Vol. 15, No. 1, pp. 119-126, 2008.

[6] Jankowski, A., Sandel, A., Sęczyk, J., Jankowska-Siemińska, B., *Some problems of improvement of fuel efficiency and emissions in internal combustion engines*, Journal of KONES Internal Combustion Engines, Vol. 9, No. 3-4, pp. 333-356, 2002.

[7] Jankowski, A., Sandel, A., Jankowska-Siemińska, B., Sęczyk, J., *Measurement of drop size distribution in fuel spray by laser method,* Journal of KONES Internal Combustion Engines Vol. 8, No. 3-4, pp. 334-345, 2001.

[8] Jankowski, A., *Some aspects of heterogeneous processes of the combustion including two phases,* Journal of KONES Internal Combustion Engines, Vol. 12, No. 1-2, pp. 121-134, 2005.

[9] Jankowski, A., *Study of the influence of different factors on combustion processes (Part two)* Journal of KONES Powertrain and Transport, Vol. 16, No. 3, pp. 135-140, 2009.

[10] Leżański, T., *Badania system spalania w silniku ZI o półotwartej komorze spalania,* Praca doktorska, Politechnika Warszawska, Wydz. MEiL, Warszawa 2011.

[11] Leżański, T., Wolański, P., *Badania nowego systemu spalania dla silników o zapłonie iskrowym z półotwartą komorą spalania,* Journal of KONES Powertrain and Transport, Vol. 14, No. 3, 2007.

[12] Leżański, T., Sęczyk, J., Wolański, P., *Influence of ignition advance angle on combustion in internal combustion spark ignition engines with semi open combustion chamber,* Combustion Engines- Silniki Spalinowe, No PTNSS-2009-SC-169, 2009.

[13] Leżański, T., Sęczyk, J., Wolański, P., *Badania wpływu parametrów konstrukcyjnych na pracę systemu spalania dla silników o zapłonie iskrowym,* Journal of KONES Powertrain and Transport, Vol. 16, No. 4, 2009.

[14] Leżański, T., Sęczyk, J., Siwiec, S., Wolański, P., *Zastosowanie fotografii szybkiej w badaniach procesu zapłonu w silnikach o zapłonie iskrowym z półotwartą komorą spalania,* Journal of KONES Powertrain and Transport, Vol. 16, No. 4, 2009.

[15] Leżański, T., Sęczyk, J., Wolański, P., *Badania systemu spalania z półotwartą komorą spalania w silniku produkcyjnym o zapłonie iskrowym,* Journal of KONES Powertrain and Transport, Vol. 16, No. 3, 2009.
[16] Leżański, T., Sęczyk, J., Wolański, P., *Some Problems of Combustion System Operation with Semi-Open Combustion Chamber for Spark Ignition Engines*, Journal of KONES Powertrain and Transport, Vol. 17, No. 4, 2010.
[17] Leżański, T., Sęczyk, J., Wolański, P., *Efekty zastosowania nowego systemu spalania w produkcyjnym silniku tłokowym o zapłonie iskrowym,* Combustion Engines – Silniki Spalinowe, No. 3/2011 PTNSS-2011-SC-021.
[18] Leżański, T., Sęczyk, J., Wolański, P., *Research of Flame Propagation in Combustion System with Semi-Open Combustion Chamber for Gasoline SI Engines*, Journal of KONES Powertrain and Transport, Vol. 18, No. 3, 2011.