RESEARCH OF FLAME PROPAGATION IN COMBUSTION SYSTEM WITH SEMI-OPEN COMBUSTION CHAMBER FOR GASOLINE SI ENGINES

Tomasz Leżański, Janusz Sęczyk, Piotr Wolański

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

Abstract

Some results of visualization researches of combustion system with divided, semi – open combustion chamber for SI engines, using rapid compression machine (RPM) and experimental visualization engine (EVE) are presented in his paper. Short description of combustion system operation, description of test stands and research equipment can be found in the paper. The tests were performed at stoichiometric ratio natural gas-air and propane-air mixtures. A few the most characteristic of results are shown; to explain how should be operate the combustion system, to yield the better performance. They are compared the research results (photographs of combustion sequence, diagrams of in-cylinder pressure histories) during visualization testing with using RCM and EVE. During RCM testing we obtained the combustion photographs in the plain pass in cylinder axis but during ECE testing at the plain perpendicular to the cylinder axis. All researches shown that the best performance are yielded when a spark advance angle (ignition timing) is such selected that stream outflow prechamber to main combustion chamber starts when the piston is at TDC and it has adequate energy to travel a main combustion chamber with higher velocity than burning velocity in quiescent chamber. Then the shortest time of combustion, the highest peak pressure in the cycle and bigger useful working are yielded. The impact of spark advance angle on flame propagation process into combustion chamber in extreme cases has been analyzed too.

Keywords*: SI engines, engine combustion systems, combustion process visualization*

1. Introduction

Obtaining high performances of internal combustion engines is possible only when it is based on the comprehensive knowledge of the mixture preparation process and the combustion mechanism. The high demands, currently required, regarding fuel consumption and exhaust emissions are impossible to meet, if we will not have adequate knowledge about the factors which affect it and how we can influence externally on it. Optical methods are helpful in understanding the mechanism of combustion. These methods have been used in studies of flame propagation process in combustion system with semi-open combustion chamber, which was developed at the Aircraft Engines Department of the Heat Engineering Institute, Warsaw University of Technology. In this system, the combustion chamber in the cylinder head of a standard engine was divided using partition on the prechamber and main combustion chamber. Electrical spark ignited the mixture in the prechamber and then the mixture in main combustion chamber was ignited by the stream of burning mixture and radicals, flowing out from the prechamber. It was assumed that the stream velocity is greater than the flame front velocity in the standard combustion chamber, causing that the cycle of engine operation is closer to the theoretical engine cycle.

As a result, higher combustion efficiency, better performance and reduced exhaust emissions should be obtained. This combustion system was used in order to shorten combustion time in the engine combustion chamber and to obtain specific effects resulting from the shortening of the combustion process. Selection of factors and understanding how they affect the combustion process was therefore a key problem of this study. The prechamber volume to total combustion chamber volume ratio, the diameter of the orifice (or orifices) in the partition separating prechamber from main combustion chamber, the place of ignition in prechamber and ignition advance angle were assumed to be the most important parameters. The researches were performance using a rapid compression machine (RCM) and an experimental visualization engine (EVE), in which good optical accesses into the combustion chamber were provided. Sequential photographs of the combustion process in the cylinder axis plane were obtained in the case of RCM. Simultaneously pressure measurements in the combustion chamber were conducted. As a result of these studies the influence of various factors on the flame propagation in the combustion chamber and the system performance as well as the ability to influence engine regulatory parameters, and engine control was determined. In the study final effects were evaluated using a production engine, which also yielded much better performance. In the studies, using the RCM and EVE, it was found that obtaining the most beneficial effects need to choose the appropriate system parameters and, above all, the proper selection of ignition advance angle, which depends not only on the combustion system parameters (prechamber volume, orifice diameter in the partition, location of ignition point), but mainly on the engine operating parameters (rotational speed, load, ambient conditions). Moreover, the ignition advance angle is the only parameter that can be changed during engine operation and can be adjusted automatically, also with the use of electronic devices. The idea of system operation is based on the division of the combustion chamber of a standard engine on the prechamber, with ignition source place inside it, and main combustion chamber, and on assumption that the stream will be flowed out from prechamber with velocity bigger than flame front velocity in standard combustion chamber. After electrical spark ignition the pressure in prechamber increases faster than that in the main combustion chamber. When the pressure difference reaches the relevant value, the stream of burning mixture and the radicals starts to flow out through the orifice in the partition from the prechamber into the main combustion chamber, from which the mixture in the main combustion chamber is ignited. As a result, the burning time (including prechamber and main combustion chamber) is shorter than that of standard combustion chamber. Thus, the higher maximum pressure in the engine cycle and bigger expansion work, that is the higher efficiency of heat conversion into mechanical work, can be obtained.

2. Test stands and apparatus

Test stands for study of flame propagation process with RCM and EVE are shown in Fig. 1 and 2, respectively. Description of test stands and apparatus can be found in references [1, 3]. Schlieren system was used to visualize combustion process. Schlieren photographs were taken using drum camera on black and white film of high sensitivity with a frequency of 5000 Hz. Simultaneously with the photographs registration; the pressure measurements in the combustion chamber (engine indication) were performed. Connecting rods from three cylinders were removed and replaced by the relevant masses to keep the crankshaft system balanced, while on one of the cylinders the experimental cylinder and cylinder head were mounted. Inside the cylinder the test piston, equipped with special optical glasses, was placed. Also in the cylinder head the optical glass window and a mirror plane were mounted to allow the transfer of images from inside the combustion chamber to the drum camera, using Schlieren system.

Because of application of the optical system for photographing combustion process in the engine, new fuelling and exhaust systems, completely different than those in the standard engine, were developed. Operation time was very limited because the soot, coating the surface of optical windows, made impossible to visualize combustion process for a long time.

Schematic of the optical system is shown in Fig. 3.

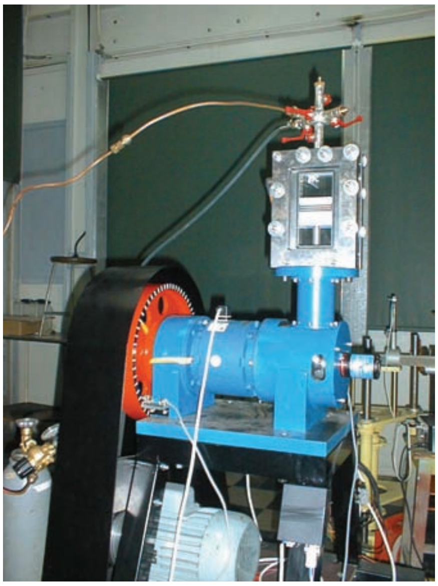

Fig. 1. View of RCM in test stand

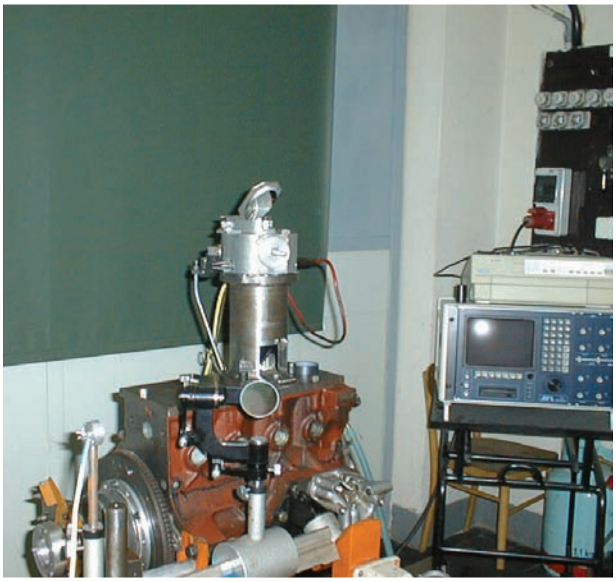

Fig. 2. View of EVE in test stand

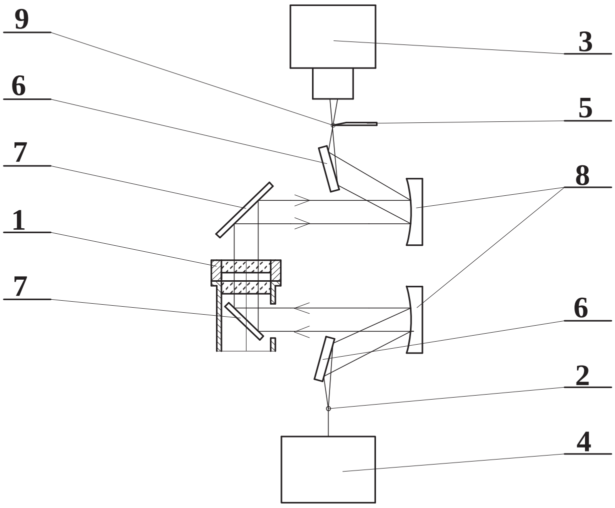

Fig. 3. Schematic of optical Schlieren system 1- combustion chamber, 2,9 - focus, 3 – drum camera, 4 – light source, 5 – optical knife, 6,7 – plane mirrors, 8 – hemispherical mirror

3. Flame propagation in the rapid compression machine (RCM)

Influence of prechamber volume (expressed as a percentage of the total combustion chamber volume), diameter of the orifice in the partition, ignition place and ignition advance angle on combustion process with use of RCM was investigated. On photographs, obtained in the cylinder axis plane, differences in the flame propagation for different configurations are shown. These differences are very large, as reflected in the course of pressure, values of the maximum pressure cycle and compression and expansion works.

The article presents extreme cases that allow a better understanding of differences in the test results. Course of the flame propagation in the system with the following parameters: initial prechamber volume - 28% (relative to the total combustion chamber volume), diameter of orifice in the partition - 3 mm, ignition on the wall of the combustion chamber, ignition advance angle - 10^0 CA BTDC and 45º CA BTDC was analyzed. These test parameters are well correlated with parameters of the system tested using EVE. Fig. 4 shows the flame propagation for ignition advance angle of 10º CA BTDC.

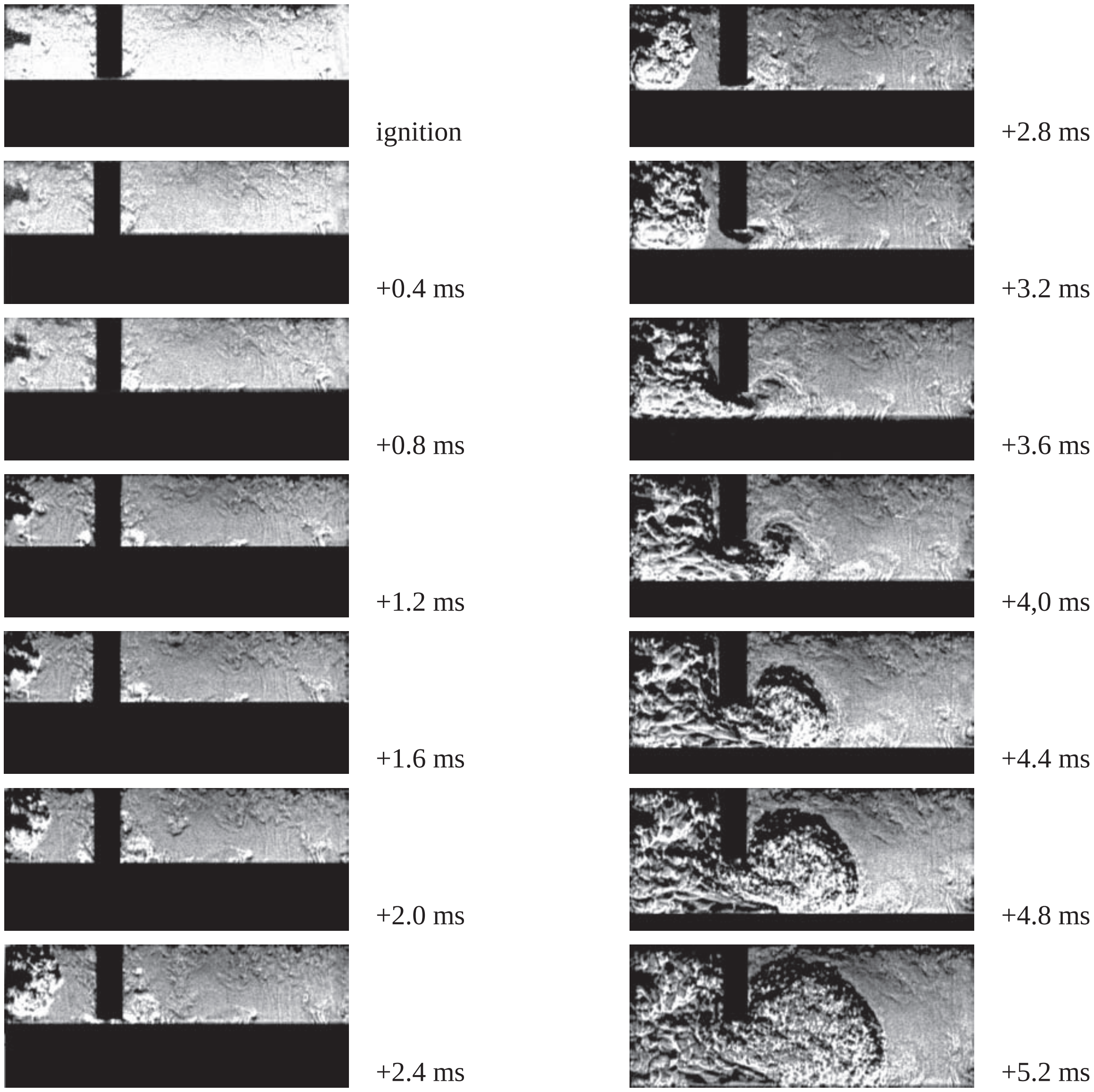

Fig. 4. Combustion process in a model combustion chamber during the tests using RCM: V_{kw} = 28%, d = 3 mm, ignition at the prechamber wall, $\varphi_{wz} = 10^{o}$ CA BTDC

Combustion process inside the prechamber begins at the time when changes in combustion chamber volume are minimal. It is yet too slow, so the pressure difference between the prechamber and main combustion chamber, when the piston is close to TDC, is not large enough to cause the gas outflow from the prechamber to main combustion chamber through the orifice in the partition. The gap between partition and piston crown, after a time of 2.4 ms from ignition, begins to grow rapidly and its cross-section area for the flow is many times larger than the area of the orifice in the partition. Thus, when the pressure difference between the prechamber and main combustion chamber is big enough, stream of combustion products and burning mixture flows through the gap, practically, between the partition and the piston crown only. The mixture outflowing from the prechamber through the gap is swirled at the edge of the partition in such direction that flame propagation in main chamber is broken. The slight difference between burning time in standard combustion chamber and tested combustion chamber is due to increase turbulence of charge. Furthermore, low values of maximum pressure and expansion work are obtained. On the indicator diagram, shown in Fig. 6, it can see two peaks of pressure course, the first, when the piston reaches the TDC position, of value much greater than the compression pressure without combustion, and the second, approximately at 50º CA BTDC. It shows that only in the angles range of 40º-50º CA BTDC increase in pressure caused by combustion was greater than the pressure drop caused by decompression. The burning at this configuration system (φ_{wz} = 10º CA BTDC) is slow, causing increase of heat exchange with environment and reduce expansion work. Fig. 5 shows the combustion course for φ_{wz} = 45º CA BTDC for the same others system configuration parameters, when ignition was placed at TDC.

Ignition appears very early in comparison with the case described earlier, when the combustion chamber volume was still very big. Combustion inside the prechamber developed when combustion chamber volume was decreased and compression pressure was rapidly increased. Before the piston has reached TDC position and the gap between the partition and the piston crown was closing, after a period of approximately 2.8 ms, the pressure difference between the prechamber and the main combustion chamber was still large enough, that there was a slight outflow of burning mixture through the gap. But it was small flow, because the gap was quickly closed and the outflow took place through the orifice in the partition, approximately 3.6 ms after the ignition. Because the whole prechamber was

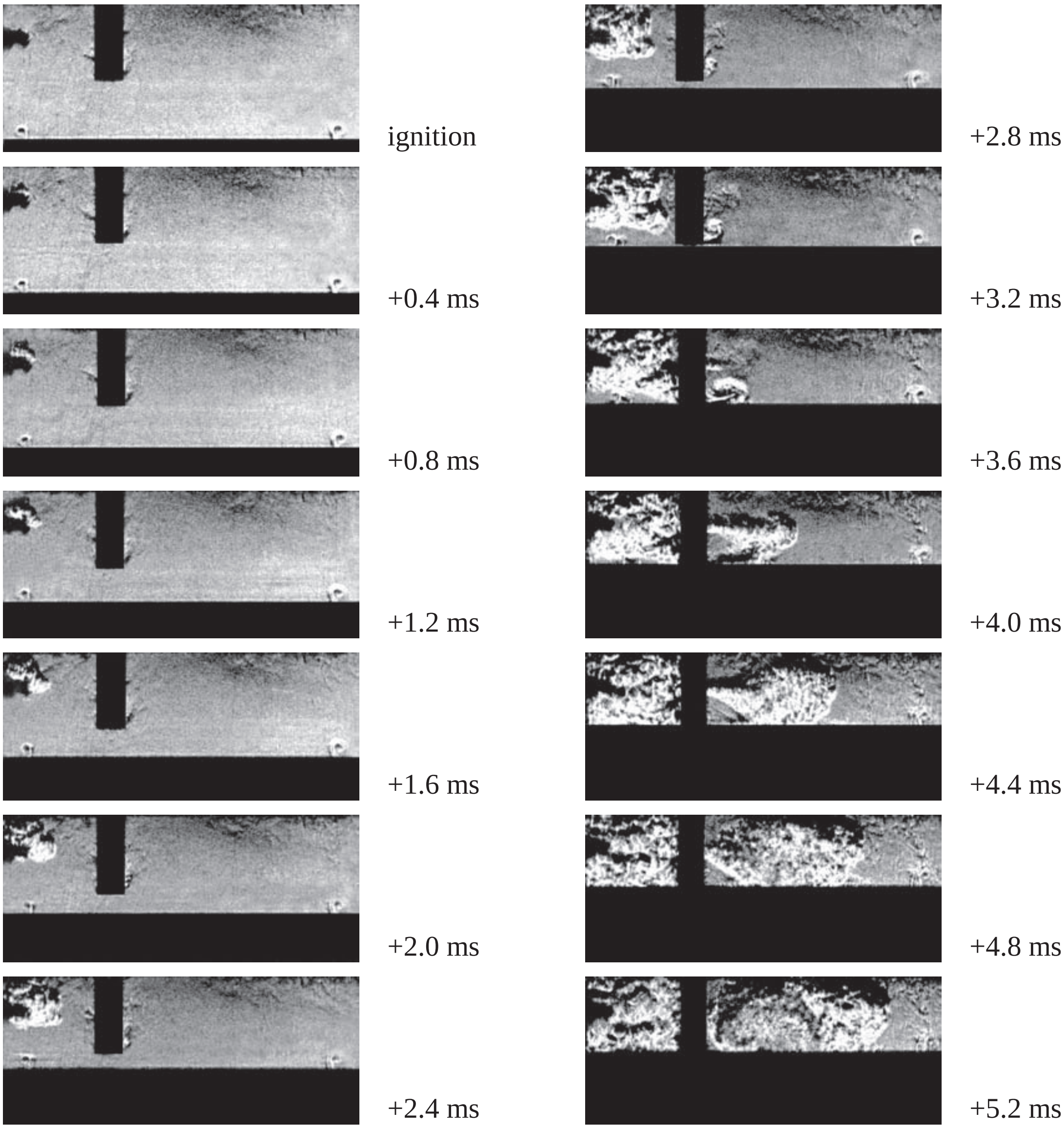

Fig. 5. Combustion process in a model combustion chamber during the tests using RCM: V_{kw} = 28%, d = 3 mm, ignition at the prechamber wall, $\varphi_{wz} = 45^0$ CA BTDC

covered by the combustion process, the pressure difference between the prechamber and main combustion chamber was a big, so the stream travelled fast through the main chamber igniting successive layers of the mixture. Swirl, which occurred a little bit earlier on the edge of the partition, was weak and it was absorbed by the stream, outflowing with high energy through the orifice. The steam velocity decided substantially on the combustion velocity in the main combustion chamber. Indicator diagram (Fig. 6) shows that the high value of maximum pressure and high value of expansion work were obtained. In the case when φ_{wz} = 45º CA BTDC, increase in compression work in relation to other cases and simultaneous much bigger increase of expansion work can be seen on indicator diagram. Fig. 6 shows courses of pressure in the combustion chamber for two values of ignition advance angle φ_{wz} = 10º CA BTDC and 45º CA BTDC. Even visually it can be estimated that if the value of φ_{wz} = 45º CA BTDC, the area, represented compression work, was slightly bigger, while the area, represented expansion work is significantly larger than those for φ_{wz} = 10º CA BTDC. As a result, the effective work and combustion efficiency were much higher.

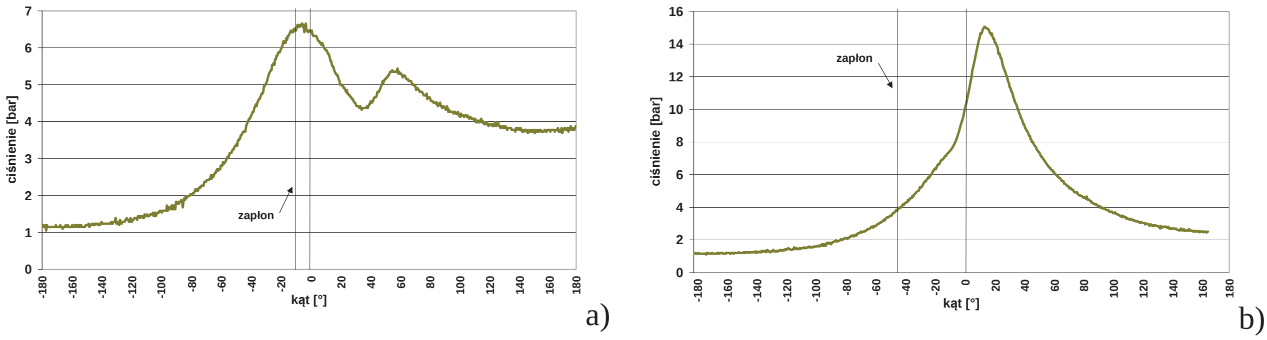

Fig. 6. Comparison of pressure changes in the model combustion chamber during the test using the RCM for two values of the ignition advance angle: a) φwz = 100 CA BTDC and b) φwz = 450 CA BTDC Vkw = 28%, d = 3 mm, igniting at the prechamber wall

In Fig. 7 comparison of displacement curves of the flame front in the combustion chamber during the test using the RCM is presented. The higher combustion velocity and also more uniform combustion process are clearly visible for φ_{wz} = 45º CA BTDC. For comparison, diagram of the flame front displacement in the model combustion chamber of standard engine was also presented.

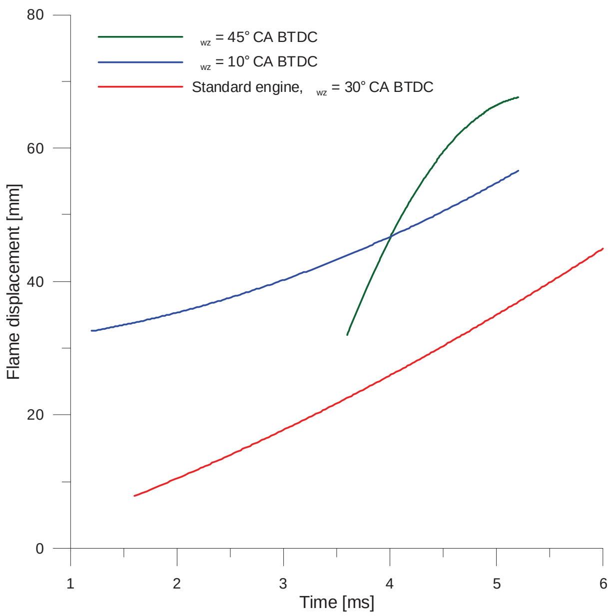

Fig. 7. Graphs of the flame front displacement for two different values of the ignition advance angle: φ_{wz} = 10^0 CA BTDC and 45^0 CA BTDC V_{kw} = 28%, d = 3 mm, ignition at the prechamber wall

4. Flame propagation in the experimental visualization engine

During testing with the EVE the flame propagation in the prechamber and main combustion chamber in the plane perpendicular to the cylinder axis were investigated, while in the case of application of RCM in the plane passing through the cylinder axis. The combustion chamber during testing with using EVE and processes of fuelling and exhausting combustion chamber were more similar to those found in production engines. In the paper two extreme examples of combustion behaviour for low and high values of the ignition advance angle are presented only. Researches with using the RCM have shown that the combustion process is the most correct when the stream of burning mixture flows from the prechamber into the main combustion chamber through the orifice in the partition only, it is, when the piston at the TDC. Then the most effective work and the most combustion efficient are obtained. Based on test results obtained with the RCM and design possibilities, the prechamber of V_{kw} = 30% (relative to the total volume of the

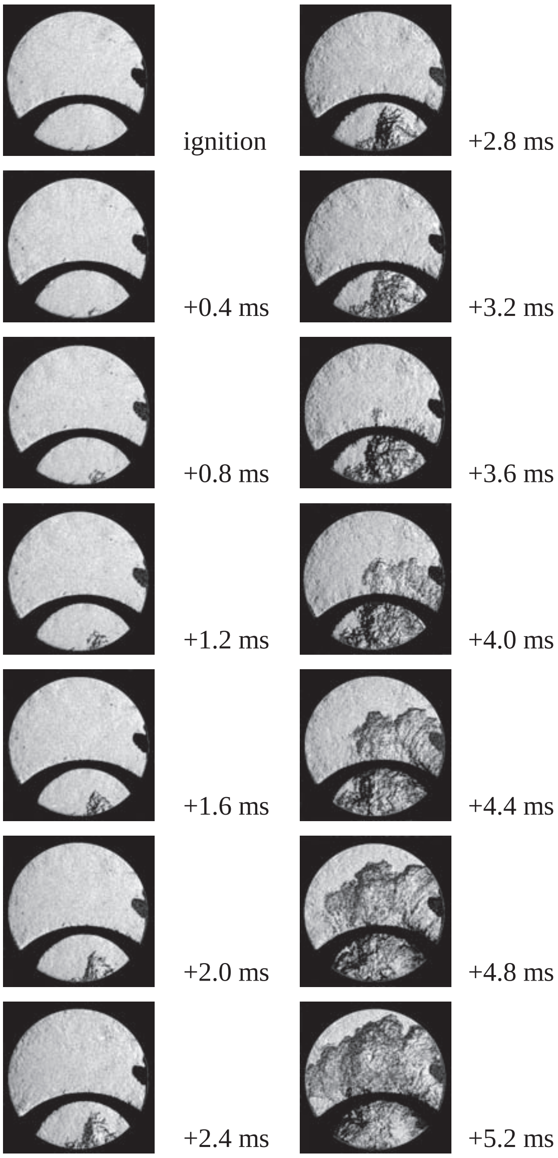

Fig. 8. Flame propagation in the prechamber and main combustion chamber of the experimental visualization engine V_{kw} = 30%, d = 3 mm, igniting at the prechamber wall, $\varphi_{wz} = 0^0$ CA BTDC

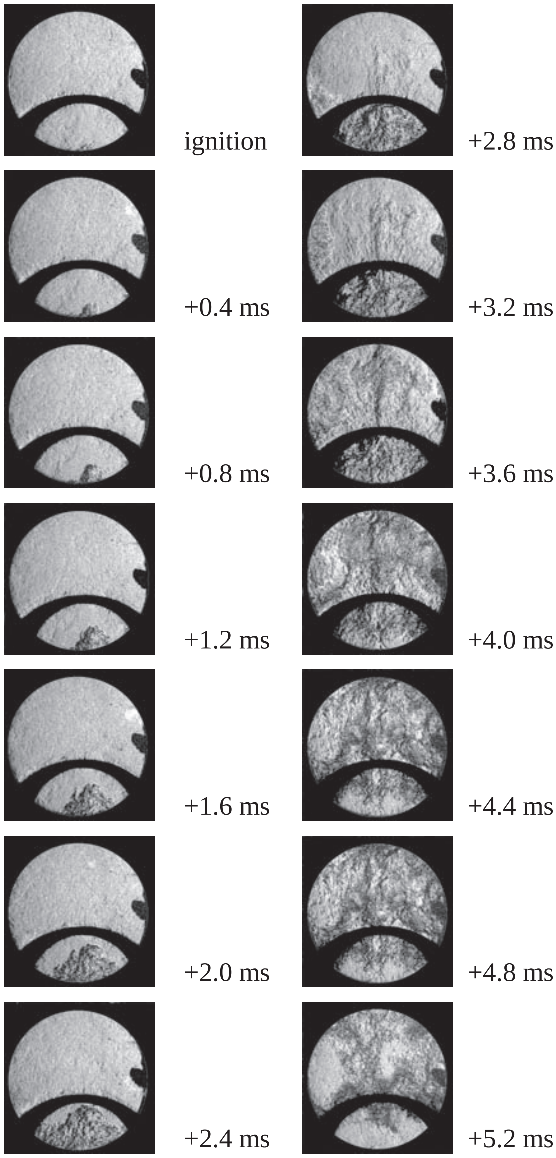

Fig. 9. Flame propagation in the prechamber and main combustion chamber of the experimental visualization engine V_{kw} = 30%, d = 3 mm, igniting at the prechamber wall, $\varphi_{wz} = 27^0$ CA BTDC

combustion chamber), orifice diameter in the partition d =3 mm and ignition at the prechamber wall were done. Two cases: the first, when the ignition advance angle: φ_{wz} = 27º CA BTDC and the second, when the piston was at TDC, were analyzed. Under these conditions, there were extreme values of system performance. Fig. 8 shows the flame front propagation when ignition starts when the piston reached TDC, and Fig. 9 when the ignition advance angle φ_{wz} = 27º CA BTDC. Comparison of photographs in these figures shows, that when φ_{wz} = 27º CA BTDC combustion process in the prechamber proceeded faster and after 2.4 ms almost 90% of the prechamber volume was occupied by flame, while in case of ignition at TDC only about 25% by volume.

Furthermore, if ignition occurred at TDC, the piston, after the time of 2.4 ms, was displaced about 0.2 mm (11º CA ATDC) from the partition, thus the gap area was large. Taking into consideration the low pressure difference also, there are no conditions for the outflow of the burning mixture through the orifice. The adequate pressure difference for the burning gas mixture outflow from the prechamber into the main chamber occurred only between 3.2 and 4 ms (15º - 18º CA ATDC). Then the gap between the piston crown and the partition is so large that its cross-section area is many times greater than the surface of the orifice in the partition, thus the flow is practically through the gap only. In the Fig. 10 indicator diagrams for the ignition advance angle φ_{wz} = 0º and 27º CA BTDC are presented. For the ignition at TDC it can see that up to the value of 16º CA ATDC the pressure drop caused by the expansion is greater than the pressure increase due to combustion.

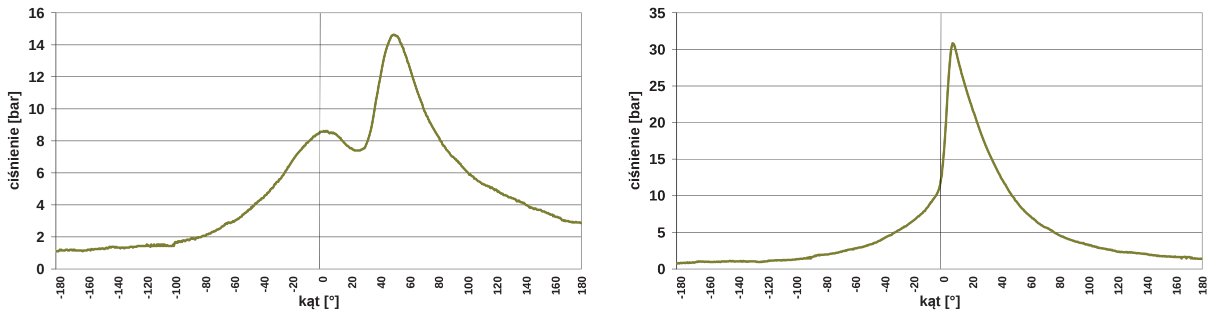

Fig. 10. High speed pressure diagrams in the combustion chamber of the experimental visualization engine visualization (EVE) 1 - φ_{wz} = 0^0 CA BTDT 2 - φ_{wz} = 27^0 CA BTDT V_{kw} = 30%, d = 3 mm, igniting at the prechamber wall

Just after 16^0 CA ATDC there is opposite situation, so increasing pressure in the chamber is observed. During this time outflow of the burning mixture and combustion products from the prechamber to the main combustion chamber can be seen. After the time of 5.2 ms, a significant part of the main combustion chamber is covered by the combustion process, but the maximum pressure on the indicator diagram was observed after about 500 CA, and up to about 15º CA ATDC course of pressure in the combustion chamber differed little only from the course of pressure in the cylinder without burning. Maximum pressure in the cycle, equal to 1.46 Mpa, was about 65% higher only than the compression pressure (0.89 MPa). When the ignition advance angle φ_{wz} = 27º CA BTDC the outflow of burning gas mixture through the orifice in the partition appeared after about 2.8 ms. After time of 3.2 ms steam front reached almost the opposite wall of the main combustion chamber, and after time of 4 ms, almost the whole combustion chamber is covered by the combustion process. Comparing these photographs with the pressure course on the indicator diagram, it can be seen that up to the 90º CA ATDC the pressure diagram is almost the same as that for the non-combustion compression, followed by a rapid increase in pressure. The maximum pressure value (3.09 MPa) is reached close to 8º CA ATDC, or approximately 7.2 ms after ignition, i.e. more than 4 ms earlier than in the case of ignition at TDC and It is 2.1 times higher than that in the case of ignition TDC. The biggest difference is observed for the value of the working area. Although in the case of ignition at φ_{wz} = 27º CA BTDC the working area during the compression stroke is slightly larger than that for ignition at TDC, but the expansion working area is much higher what makes the effective work to be about 60% higher in the case of φ_{wz} = 27º CA BTDC. It shows how significant results can be obtained if the proper selection of timing advance is made. From analysis of maximum pressure values, obtained for different ignition advance angles, it can be concluded that there is a relatively narrow range of ignition advance angle values, where the high values of both, the maximum pressure and maximum effective work are obtained, and that these maximum values are very clear.

5. Conclusions

1. Studies of flame propagation using the combustion system with semi-open combustion chamber, designed for SI engines, carried out using a rapid compression machine and an experimental visualization engine, allowed to interpret the phenomena occurring during combustion process.
2. It was stated that the assumed mechanism of combustion in this system can be achieved only when the outflow of burning mixture and exhaust gases from the prechamber to the main combustion chamber, through the orifice in the partition, starts when the piston is near TDC position (approximately ± 10^0 CA in relation to TDC).
3. If the pressure difference between the prechamber and the main combustion chamber, allowing the outflow from the prechamber into the main combustion chamber is achieved for the bigger value of crank angle, the cross-section area of the gap between the partition and the piston crown is much larger than the orifice area in the partition, so that the outflow occurs through the gap, what will be reflected in the deterioration of the system performance.
4. A stream of burning mixture and exhaust gases outflowing from the prechamber to the main combustion chamber through the orifice in the partition should travel through the main combustion chamber with a velocity greater than the flame front velocity in the standard combustion chamber, what will be resulted in performance improvement.
5. A key problem for the proper operation of the combustion system with semi-open combustion chamber is to choose the appropriate value of ignition advance angle, depending on engine operating parameters (especially the engine speed and load) and combustion system parameters (prechamber volume, diameter of the orifice in the partition, ignition place), which, at the moment, is possible by experimental testing only.
6. Visualization researches enable to determine the direction of changes in the design and structure of the system with semi-open combustion chamber, necessary for achieving positive results of the system operation.

References

[1] Leżański, T., Sęczyk, J., Wolański, P., *Effects of Application of New Combustion System in a Commercial Spark Ignition Engine (in Polish)*, Combustion Engines – Silniki Spalinowe, No. 3, (146), Radom 2011.

[2] Leżański, T., Sęczyk, J., Wolański, P., *Some Problems of Combustion System Operation with Semi-Open Combustion Chamber for Spark Ignition Engine*, Journal of KONES Powertrain and Transport, Vol. 17, No. 4, pp. 287-294, 2010.

[3] 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, pp. 365-370, Opole 2009.

[4] Leżański, T., Sęczyk, J., Wolański, P., *Research of Influence of Design Parameters on combustion System Operation for Engines* (in Polish), Journal of KONES Powertrain and Transport, Vol. 16, No. 4, pp. 265-276, 2009.

[5] Leżański, T., Sęczyk, J., Wolański, P., *Using of High-Speed Photography to Research of Ignition Process in SI Engines with Semi-Open Combustion Chamber* (in Polish), Journal of KONES Powertrain and Transport, Vol. 16, No. 4, pp. 277-286, 2009.
[6] Leżański, T., Wolański, P., *Investigation of New Combustion System with Prechamber for Spark Ignition,* 347-354.