*Journal of KONES Powertrain and Transport, Vol. 21, No. 4 2014*

**ISSN:** 1231-4005
**e-ISSN:** 2354-0133
**ICID:** 1130472
**DOI:** 10.5604/12314005.1130472

# RESEARCH EFFECTS OF NOVEL COMBUSTION SYSTEM WITH SEMI-OPEN COMBUSTION CHAMBER USING RAPID COMPRESSION MACHINE

**Tomasz Leżański, Janusz Sęczyk, Piotr Wolański**

*Institute of Heat Engineering*
*Warsaw University of Technology*
*Nowowiejska Street 21/25, Warsaw, Poland*
*e-mail: lezanski@itc.pw.edu.pl*

***Abstract***

*The combustion system with semi open combustion chamber (SOCC) was originally elaborated in Aircraft Engine Department of Warsaw University of Technology. In this system the original combustion chamber of the standard SI engine, was divided by partition in prechamber and main combustion chamber, but yet this division exists only when the piston is close to TDC, on the contrary by the rest of the cycle the chambers are fully open. The system operation mechanism, the visualization research results, the high speed changed of the pressure measurements, was presented in this paper. The influence on the system performances of the different combustion systems parameters: the prechamber volume, the nozzle hole diameter in the partition, the ignition place, the compression ratio, and the ignition advance angle (IAA), on the basis of the research results, using rapid compression machine was presented in this paper. All research results show, that the best results of the system operation can be obtained if the stream outflow from prechamber to main combustion chamber starts when the piston is at TDC, and if the stream energy will be so big to displace all main combustion chamber before the clearance between partition and piston crown was opened. If the system operated correctly, the combustion time shortening, the growth of the maximum cycle pressure, and the combustion efficiency increase were obtained.*

***Keywords**: internal combustion engines, spark ignition, combustion processes, engine combustion systems, combustion process visualization*

## 1. Introduction

The combustion system with semi-open combustion chamber belongs to combustion systems with divided combustion chamber and it is the answer to the shortcomings of the systems with divided combustion chambers. Relatively low exhaust emissions and smooth operations are advantages of the standard systems with divided combustion chambers, in comparing to open combustion chamber systems, but some lower engine performances, higher fuel consumptions, problems with scavenging of exhaust gases, and defects suffering from higher thermal loads are their faults. To avoid of these faults, the combustion system with semi-open combustion chamber (SOCC) was proposed. The principal difference in operation, between standard combustion system, with divided combustion chamber (SDCC) and system SOCC consists in this, that separation of the prechamber and main combustion chamber (MCC), in the novel system, exists only when a piston is near top dead centre (TDC). Therefore the problem with scavenging of the exhaust gas is avoided, but burning time in combustion chambers (prechamber and MCC) is shorter, the maximum pressure is higher which, in turn, increase the effective expansion ratio and consequently increases the engine thermal efficiency, so, engine efficiency and performances are higher than in combustion systems with semi-open combustion chambers [24-24].

Obtaining high performances of internal combustion engines is not now possible if it is not based on the comprehensive knowledge of the mixture preparation process and the combustion mechanism [3-12]. The high demands, currently required, regarding the fuel consumption and exhaust emissions are impossible to meet, if we will not have adequate knowledge about factors influencing on it and how we can influence externally on it. It requires relevant get in combustion mechanism. The optical methods can be helpful in their recognition. [1, 17, 21]

The primary researches of the SOCC system were performed in the modified constant volume bomb, which was equipped in specific driving mechanism, assures some small piston movement [23]. The aim of the piston movement was to make time dependent magnitude of the clearance between piston crown and partition, but not compress the charge in the bomb. The research results confirmed the system operation principle and possibilities obtaining of the positive effects. Therefore, the rapid compression machine (RCM), modelling the piston movements in the engine, as elaborated and manufactured. The researches of the combustion mechanism were carried out, take into consideration the different combustion systems parameters, using RCM, visualization methods and high speed pressure measurements. The research results of the combustion system with SOCC were very satisfactory and were presented at different meetings [1, 13, 21]. The essential importance for regular operation of this system with SOCC has the mixture preparation process, especially fuel atomization, evaporation and mixing [3-9]. The research results conducted using RCM, show that the air/fuel ratio (equivalence ratio) must be hold in the precisely define limits, because the change of the equivalence ratio leads to the changes of the combustion mechanism, which decide about engine performances, first of all: rated power, fuel consumption and exhaust emissions.

## 2. Experimental apparatus and procedure

### 2.1. Test stand

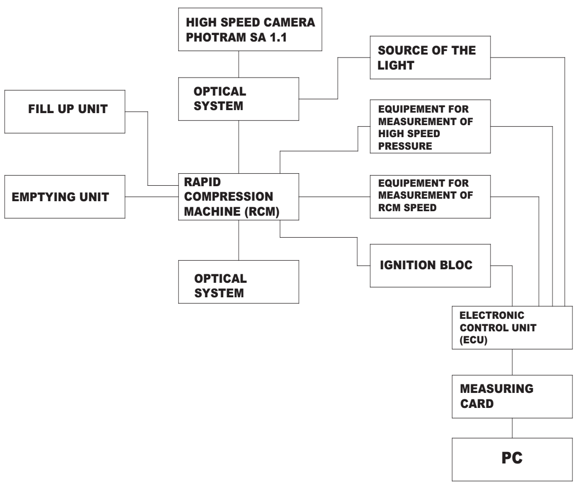



*Fig. 1. Bloc schema of RCM test stand*

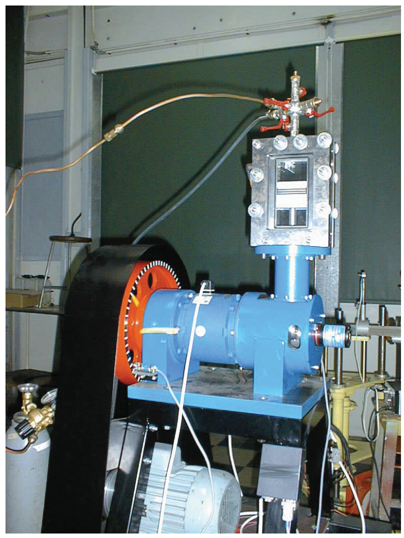


*Fig. 2. View of RCM test stand*

The block schematic of test stand is shown on Fig. 1, but their view on Fig. 2. The stand includes rapid compression machine (RCM), ignition block, equipment for fresh mixture fill up and emptying of exhaust gases, measuring equipment for measure high speed changed pressure and RCM speed, optical system for creation of parallel light stream, high-speed camera, measuring card PC computer with large memory. The computer stores and processes research results, particularly images and high-speed pressure histories. The fill up with fresh mixture of combustion chamber is realized from pressurized bottle before test. The natural gas/air, homogenous, stoichiometric mixture was prepared in one bottle for all tests, to avoid of discrepancies in the mixture composition during successive tests. The natural gas contains above 96 percent of methane. The vacuum pump was used for emptying exhaust gases after tests. The electric spark ignition was used, to ignite the fresh mixture in combustion chamber.

## 2.2. Rapid compression machine

A rapid compression machine is an instrument to simulate a working single cycle of piston internal combustion engines without induction and exhaust strokes, to allow the study of combustion under more favourable conditions than those in real engines. The RCM used for this research were originally built in Aircraft Engine Department of Heat Engineering Institute of Warsaw University of Technology. The central unit, the electric motor of 3 kW, the external belt transmission, the electromagnetic clutch and the flywheel are parts of the RCM. The central unit includes the crank mechanism, the parallelepiped combustion chamber with easy changed quartz windows on a front and a rear walls, the rectangular piston, the connecting and sliding rods, the cylinder head with equipment for fill up and emptying combustion chamber and pressure transducer mounting.

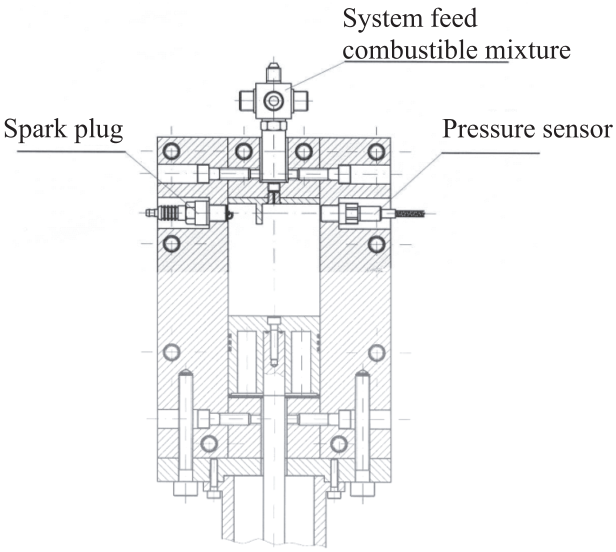



*Fig. 3. Combustion chamber design*

The design of the RCM combustion chamber was presented on Fig. 3. A singularity used RCM, in comparison with another one, is crank mechanism used to drive working piston, so this RCM operates similarly as a standard piston engine. Elaborated design allows obtaining required of the RCM speed in short time after switch on the electromagnetic clutch.

## 2.3. Optical system

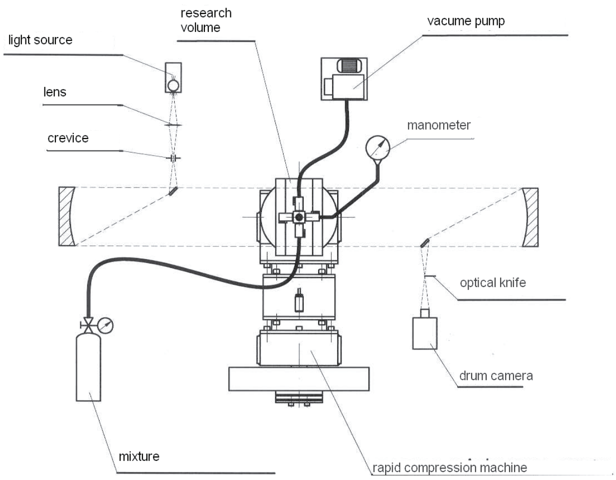



*Fig. 4. Research optical system*

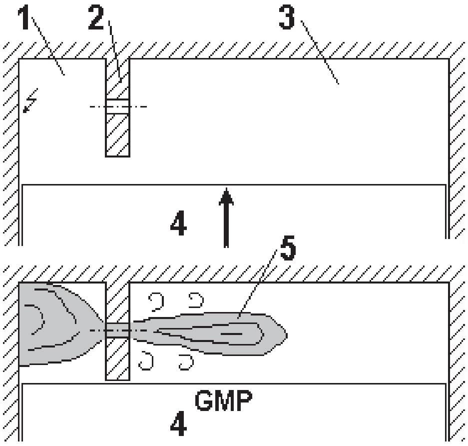
This system is intended to create parallel luminous flux, to illuminate the research volume. Fig. 4 shows this system which includes: the plain and concaves mirrors, the lenses, the optical knife and light source (light emitting laser diode). The Photram SA 1.1 camera was used to register the combustion images with frequency of 5000 frames per second and exposition time 50 μs, but in earlier tests, the photographic drum camera was used.

### 2.4. Pressure measurements

The system of high speed pressure measurements includes: the piezoelectric transducer Kistler 6053A (pressure range 0-250 bar, sensitivity – 6pc/bar, natural frequency 120 kHz, linearity ±0.5%, temperature range (223-623 K), the amplifier Kistler 5011A, the crank angle encoder PFI 80. The pressure histories, and the combustion images versus time were registered, which make possible the comparisons of research results.

### 2.5. Operation of the system with semi-open combustion chamber

Figure 5 shows operation of the combustion system with semi-open combustion chamber. In this system, a standard combustion chamber in cylinder head of the spark ignition (SI) engines was divided in the prechamber and main combustion chamber with partition. Prechamber has a volume a few times less than a main chamber. The division of combustion chamber in the prechamber and main combustion chamber exists when a piston is near TDC only.




*at 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. 5. Operating principle of the combustion system with semi-open combustion chamber*

Therefore, this system was assigned the combustion system with semi-open combustion chamber. When the piston is far from TDC a big clearance between the partition and the piston crown opens. So, the burning mixture may flows free between prechamber and main combustion chambers. There is one (or more) orifice hole in the partition. Through these holes, the burning mixture from the prechamber should outflow to main combustion chamber when the piston is near TDC. The mixture is ignited in prechamber using an electric spark plug when the piston is near TDC. Because the ignition occurs in prechamber, the pressure in prechamber during compression grows faster than in main combustion chamber. When the difference between prechamber and main combustion chamber reaches sufficient level, the mixture should outflow from prechamber to main combustion chamber through the hole in partition to ignite the mixture in main combustion chamber. When the piston is near TDC, the pressure difference, between prechamber and main combustion chamber, should achieve relevant level to enable the outflow through the hole in the partition. The stream of outflowed burning mixture should have sufficient energy to reach quickly opposite wall of the combustion chamber.

## 3. Researches results

The researches was conducted using rapid compression machine, in which the model combustion chambers were fixed, besides full volume of the prechamber and main combustion chambers was 36 $cm^3$, and it was close to the combustion chamber volume in the standard production engine, in which the testing of the engine with the SOCC system at the test stand were anticipated. The researches of the influence of the following parameters of SOCC system on combustion were conducted: the prechamber volume in percent on the full combustion chamber volume (prechamber and main combustion chamber), the nozzle hole diameter in the partition separated the prechamber from the main combustion chamber, the ignition location in the prechamber, the proportions of the combustion chamber dimension, the compression ratio (CR) and the ignition advance angle (IAA). The high-speed pressure histories and the picture movies of the combustion in the combustion chamber were obtained during each test. There results were detailed analysed and the conclusions from point of view the practical application of the SOCC system at the production engines. The drum photographic camera and the high-speed electronic digital camera were used to register the picture in the visualization researches of the SOCC system.

### 3.1. Influence of the prechamber volume

The prechamber volumes were: 10%, 20% and 28% in relation to the full volume of the prechamber and the main combustion chamber. The height of the prechamber and the main combustion chamber were identical but the length of the chambers was varied. Majority of the researches were conducted with the CR 6:1, but the researches of the influence of the CR on the combustion was conducted with different CR only.

The research results show that the time of combustion in prechamber, when the relevant pressure difference between the prechamber and the main combustion chamber is reached at which a stream start to outflow from the prechamber to the main combustion chamber through the nozzle hole in partition, and also the stream range from the prechamber volume, is depended. So, the prechamber volume decides about an optimal value of the ignition advance angle. If the prechamber volume is too small, the combustion time is short, the stream outflow is speedy, but the pressures in prechamber and main combustion chamber equalize and the stream range is small. If the prechamber volume is big, the burning time in prechamber is long and the range of the stream is greater.

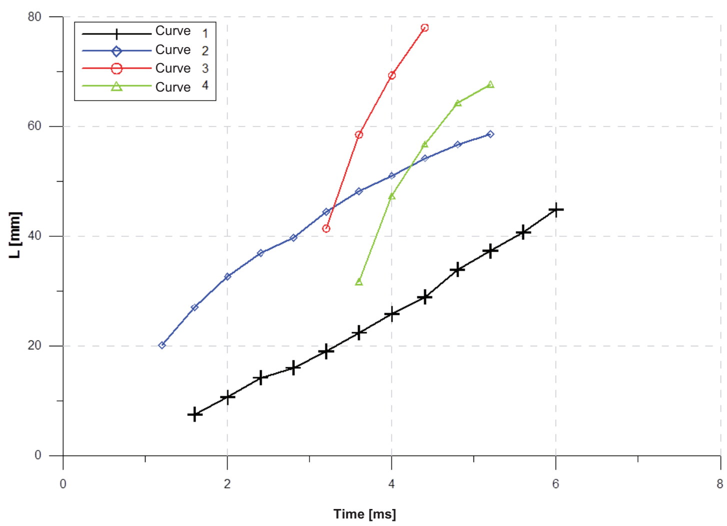



*Fig. 6. Displacement of flame fronts for different prechamber volumes and for standard combustion chamber for comparison standard chamber, 2. Vp=10%, $\varphi_{wz}=20^0$ CABTDC, 3. Vp=20%, $\varphi_{wz}=35^0$ CABTDC, 4. Vp=28%, $\varphi_{wz}=45^0$ CABTDC*

On the Fig. 6, the flame front displacements were compared for different prechamber volumes and the remaining optimal parameter values of the SOCC system (the nozzle hole diameter, the ignition placement, the IAA); for comparisons, the flame front displacement in standard combustion chamber was set up. It can be see, that the burning time in the 10% prechamber volume is more short than in comparative volume of the standard combustion chamber. However, after the outflow from prechamber the burning velocity in the main combustion chamber quickly achieves the burning velocity value in standard combustion chamber. In connection with this full burning time, in the prechamber and the main combustion chamber is shorter about 20%. It means, that in the majority part of the combustion processes about the burning velocity decides no more the displacement of the stream flame front, which is an operation principle the SOCC system but the chemical reaction velocity.

In the case of the prechamber volume, 20%, the burning time in prechamber was somewhat shorter than in comparative volume of standard combustion chamber, but comparatively longer than in the prechamber volume of 10%. However, the stream after the outflow from prechamber has big displacement velocity and after very short time, it reaches the opposite wall of the main combustion chamber. Full burning time, in prechamber and main combustion chamber was about three times shorter than in standard combustion chamber. Moreover, the highest of the maximum pressure value in the engine cycle, the high value of the useful work field, and the high combustion efficiency – higher about 4% in comparison to standard combustion chamber – are achieved.

In the case of the prechamber volume of 28%, the burning time in prechamber was comparative to burning time in comparatively volume of the standard combustion chamber. The stream outflowing through the nozzle hole in partition has a big velocity and quickly displaced into the main combustion chamber. The stream range however, was somewhat smaller than the length of the main combustion chamber, and at the final sector of the burning velocity decides the chemical reaction velocity.

The shortest time of the combustion into the prechamber and the main combustion chamber together was obtained in the case of the prechamber volume of 20%. The prechamber volume in real production engine however is depended too from design circumstances, mainly the presence of the valve timing system and real values of the ignition advance angles. If the prechamber volume is big, it require to apply big values of ignition advance angles, which influences on the efficiency decrease with the reason of the compression work increase of the exhaust gas instead to compress the fresh mixture.

### 3.2. Influence of the nozzle hole diameter

The nozzle hole diameter in the partition separated the prechamber from the main combustion chamber decides about the stream movement resistance, so, it means: when will be start the stream outflow from prechamber, which will be stream dimensions, how long will be time of the outflow and the stream range in the main combustion chamber. If the diameter of the hole is smaller the movement resistance is bigger, it requires the greater of the pressure difference between the prechamber and the main combustion chamber, to the stream can outflows. If the hole diameter are bigger, the movement resistance is smaller, so the outflow can start at smaller pressure difference. The smaller pressure difference means that the stream range can be smaller. Moreover if the hole diameter is small the stream diameter is small too and the stream is swirled at the hole edge and its range is small.

This is illustrated on Fig. 7, which it shows the numerical simulation results concerning of the flow velocity into nozzle holes in the partition, when the hole diameter have: 1 mm, 2 mm, 3 mm. The flow velocity for diameter 1 mm is 70% bigger than for diameter 2 mm, but the velocity difference for 2 mm and 3 mm is only 10%. The characteristic is the returnable flow in the hole from the main combustion chamber to prechamber, when the piston moves from TDC to BDC. This is not observed during experiments, because then the clearance between partition and piston crown is created and the returnable flow pass through this clearance. On Fig. 8 the displacement of the stream flame front, for different hole diameters in the partition for two different of the piston placement (at TDC, ant $10^0$ ATDC) is shown. It can be seen on a figure that the outflow from the prechamber to the main combustion chamber follows before the piston was at TDC, but when the piston was $10^0$ ATDC, the half of the main combustion chamber volume was embraced of the combustion process.

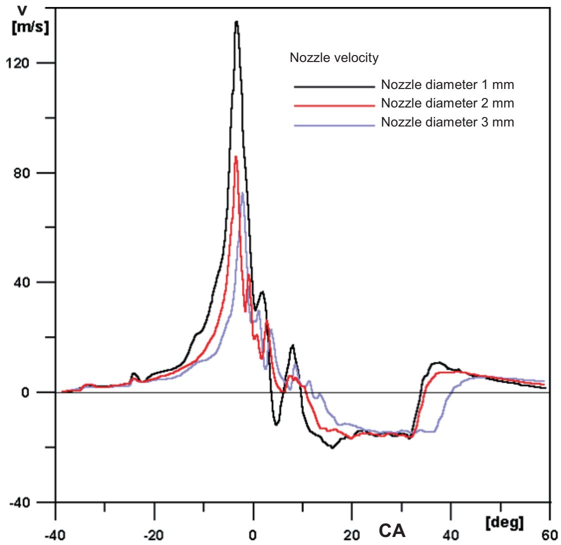



*Fig. 7. Flow velocity into nozzle holes in the partition (numerical simulation)*

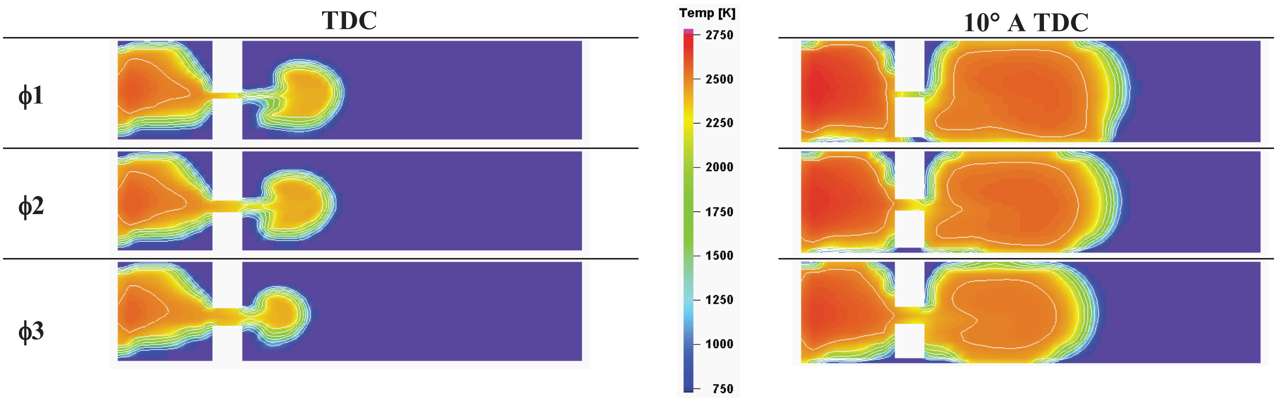



*Fig. 8. Flame front displacement for different the nozzle hole diameter, if the piston is at TDC and 100 ATDC (numerical simulation)*

After turn of the crankshaft of $10^0$ ATDC the clearance between partition and the piston crown is so big, that all streams from prechamber to the main combustion chamber outflows through this clearance instead the hole in the partition. Therefore, the stream, which outflows from the prechamber to the main combustion chamber, should already attain the opposite wall of the combustion chamber. If the stream will be outflow through the clearance, it swirls at the hole edge and will be braked the stream which earlier outflow through the hole in the partition, which can be seen on the photograph obtained during visualization researches using rapid compression machine.

The result presented on Fig. 7 and 8 were obtained using KIVA code for mathematical simulation. The experimental researches were conducted using optical visualization system, for three hole diameters in partition: 2 mm, 3 mm and 5 mm. In the theoretical and experimental works the best results were obtained when the hole diameter was 3 mm.

The courses of flame fronts on the Fig. 9 were compared, for the hole diameters 3 mm and 5 mm (the prechamber volume 20%) and for the standard combustion chamber. The range of the stream is smaller when the hole diameter is 5 mm, which it is the effect too small stream energy, the stream, which outflowed through the hole in the partition, is braked by another stream which outflowed through the clearance between the partition and piston crown.

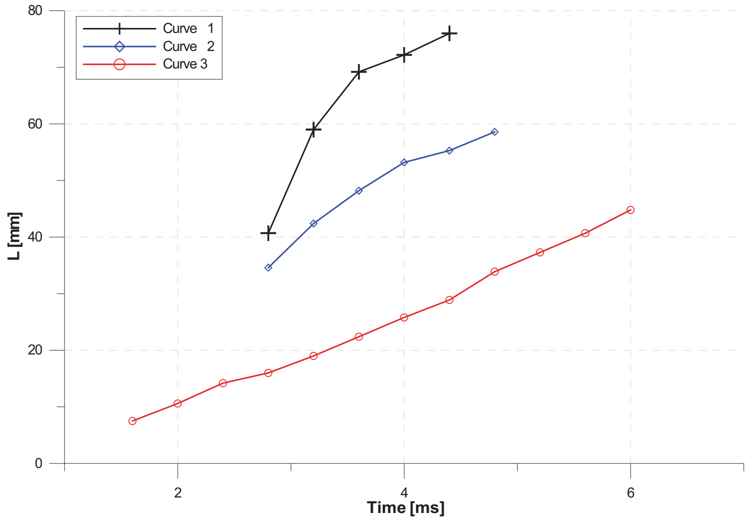



*Fig. 9. Flame front displacement for the nozzle hole diameters: 3 mm, 5 mm, and for standard combustion chamber*

### 3.3. Influence of the ignition locations

The mixture ignition takes place in the prechamber by means of the electrical sparking plug, while the spark ignition electrodes were installed variably at three locations: at the wall of prechamber, in the middle of the prechamber, and in the partition nozzle hole. The photographs on the Fig. 10 compare the combustion courses after the ignition initiation, when the spark electrodes were located in different places. It needs to draw attention that the combustion course after ignition in the prechambers of 20 and 28% was similar and depended from ignition placement. However, flame development ignition in the prechamber with volume of 10% was only a little depending on the ignition placement, in those three places.

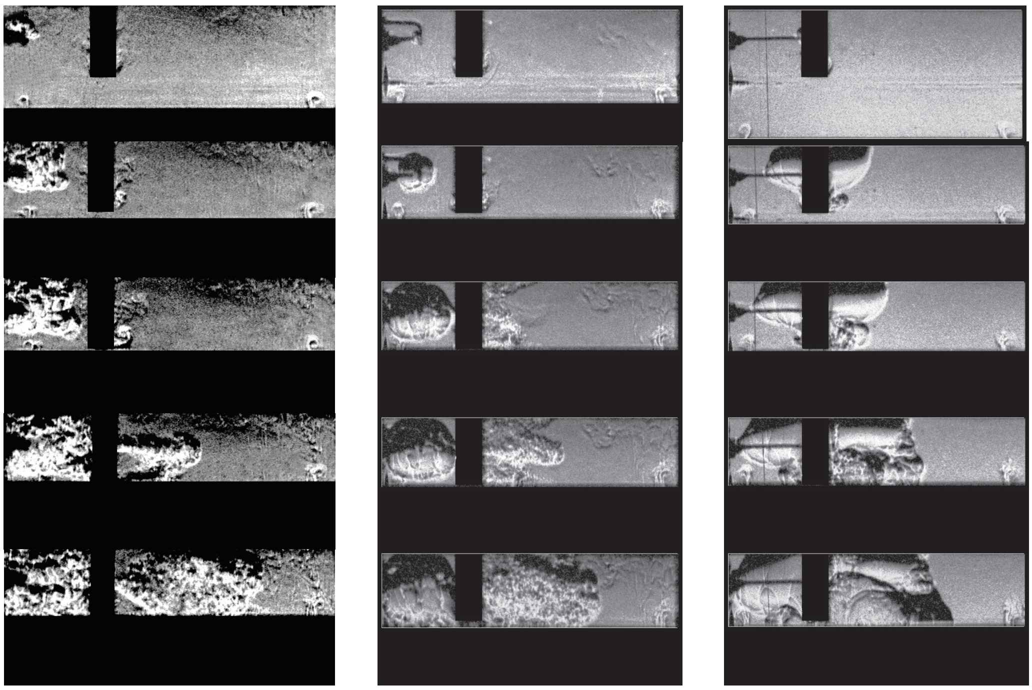


*Fig. 10. Comparison of the combustion courses after ignition initiations at different places in the SOCC combustion system: left – at the wall, middle – at the middle of prechamber, right – in the nozzle hole in the partition*

The photographs on the Fig. 10 show that in case ignition on the wall, the combustion has the turbulent character and burning time in the prechamber is the shortest. In the case of ignition in the middle of the prechamber, the flame front after ignition initiation is displaced along the sphere radius, and has spherical shape. When the flame front reaches the prechamber wall it catches their shape and is tubulised. In the result burning time in the prechamber is longer than during ignition at the prechamber wall. When ignition took place in the nozzle hole, the flame front was displaced at two directions, to the prechamber direction and to the main combustion chamber. It had laminar character and was smooth. The stream outflowed from nozzle hole was not formed, because the pressure difference between prechamber and main combustion chamber was too small. A short smaller combustion time in prechamber and main combustion chamber together is the effect simultaneously displacement of the flame fronts at two directions. So, the effect of the operation of the SOCC system was not achieved. Moreover, if the ignition place is nozzle hole, big discrepancies of the value of the maximum cycle pressure were obtained, which is joined with the small combustion turbulisation level in the combustion chambers.

### 3.4. Influence of the compression ratio and dimension proportion of the combustion chamber

In these researches, the compression ratio was varied, by the changes of the length of the combustion chambers, but their height was constant. The following compression ratio had the tested combustion chambers: 6:1, 8:1, 10:1, 12:1. When the compression ratio was bigger the length of combustion chamber was smaller. The burning velocity and maximum cycle pressure increased. If the length of combustion chamber was smaller, the burning time was shorter and smaller range of the stream, outflowed from nozzle hole was required.

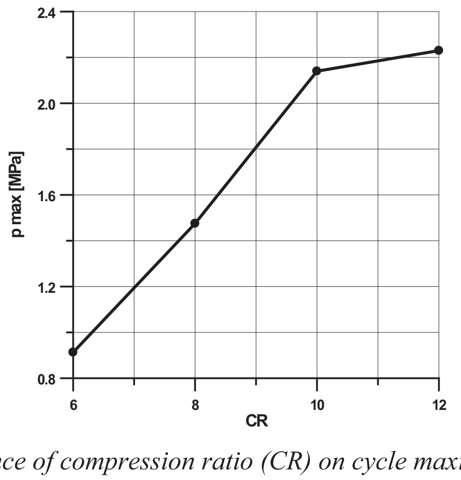



*Fig. 11. Influence of compression ratio (CR) on cycle maximum pressure*

Figure 11 shows the dependence between maximum cycle pressure value and the compression ratio, for the most profitable values of ignition advance angle, for each compression ratio. The growth of compression ratio causes substantial growth of maximum cycle pressure. Then increment of the maximum cycle pressures was bigger for smaller compression ratio; the growth of CR from 6:1 to 10:1 causes growth of maximum cycle pressure about 2.3 times, but from 10:1 to 12:1, about 4.2% only.

### 3.5. Influence of the ignition advance angle

The ignition advance angle is the only, from combustion system parameters, which can be continuously varied during engine operations. The changes of other system parameters require the engine dismantle. For each of the SOCC system parameters: the volume of prechamber, the hole diameter, the ignition place is required to choose relevant values of IAA, which it assures the best performances. It need to drove attention that the mixture composition and ambient conditions, too influence on the SOCC system operation. Therefore, to assure correct operation of the SOCC system, the maps of ignition timing have to be elaborated, for different system parameters, ambient conditions and mixture compositions, engine load and speed. These maps must be introduced to memory of electronic control unit and to control of the engine operations.

Analysing the photographs of the burning courses and measurement values of high-speed changes of the pressure in combustion chamber, it can be seen, that the IAA values had big influence on operation mechanism of the SOCC system. Only at the time, if the stream start outflows from the prechamber to the main combustion chamber, when the piston is at TDC, and the burning mixture into all prechamber is burned, the stream outflowed through the hole in the partition had the relevant energy to traverse all main combustion chamber, before the clearance between the partition and the piston crown appears. Then combustion mechanism of the SOCC system is protected; the maximum cycle pressure, the biggest work field of the indicator diagram and maximum combustion efficiency are obtained. Fig. 12 presents the combustion course in the combustion chamber when the IAA was the best choose ($V_p$=20%, d=3 mm, $\varphi_{IAA}=35^0$ CABTDC). The time to the outflow from prechamber was about 3 ms, but after 1.4 ms before the clearance between partition and piston crown appears, the stream traversed all main combustion chamber and it achieves opposite wall of combustion chamber. When the clearance opens it cause the small outflow through the clearance but it does not influence on the stream traversing.

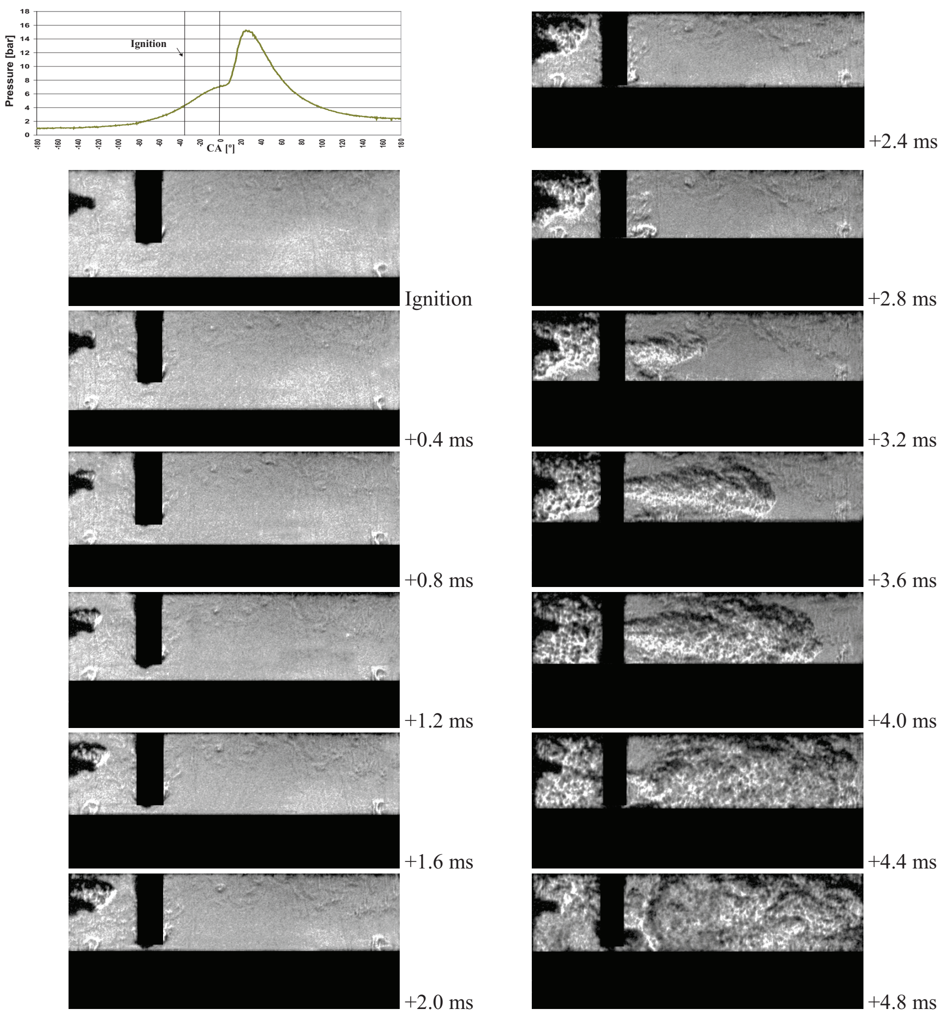



*Fig. 12. Combustion process development for the best of ignition advance angle: $V_p$=20%, d=3 mm, ignition at wall, $\varphi_{IAA}=35^0$ CABTDC*

Figure 13 presents the combustion course in the combustion chamber when the IAA was too small (Vp=28%, d=3 mm, $\varphi_{IAA}=10^0$ CABTDC). Combustion into prechamber was completed when the piston moved at BDC direction (about 3.4 ms from start of combustion and about $35^0$ CAATDC).The clearance between partition and piston crown was so big, some times bigger than cross section field of the nozzle hole, and therefore burning mixture from prechamber start to outflow through the clearance. Nearly all mixture from prechamber outflowed through the clearance. The burning mixture experienced of swirling at the edge of the partition and additionally blocked of the stream outflowing through the hole in the partition. The flame front displacement in the main combustion chamber was slow and determined by chemical reaction kinetics but not by stream displacement. After about 4.8 ms from combustion start, when in case presented on Fig. 12 the stream reaches opposite wall, the stream displaces about 61% the length of the combustion chamber.

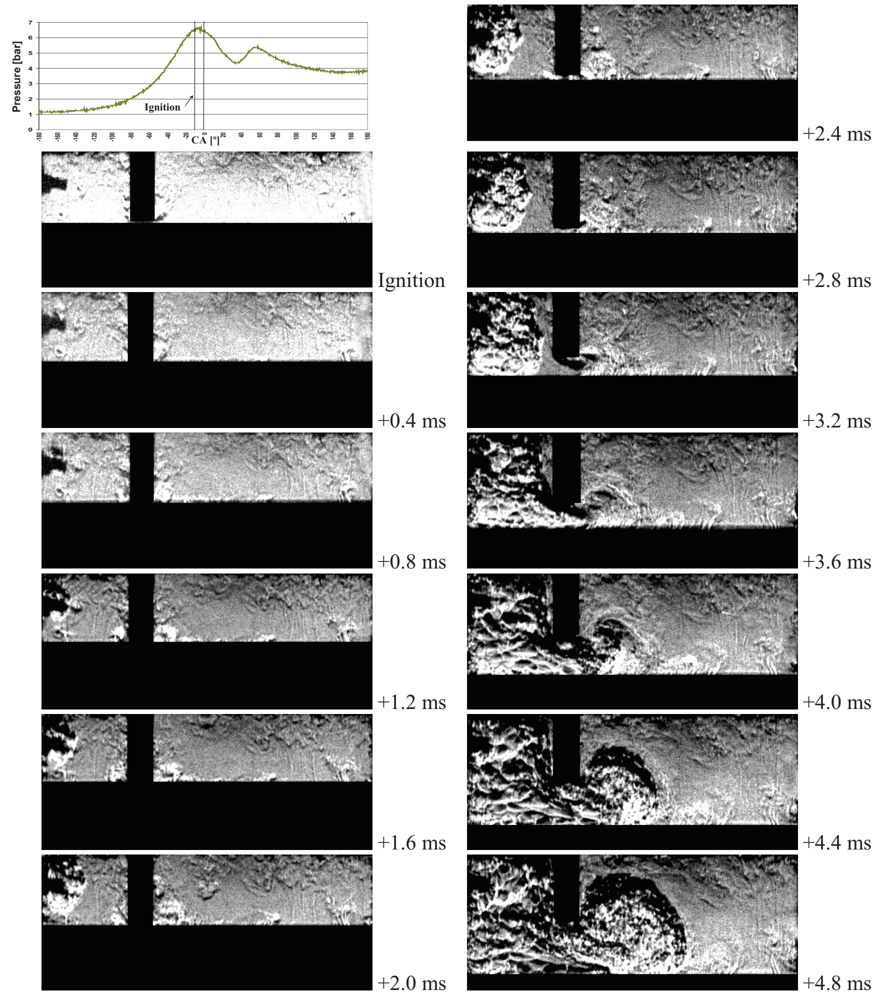



*Fig. 13. Combustion process development for too small of the ignition advance angle: Vp=28%, d=3 mm, ignition at wall, $\varphi_{IAA}=10^0$ CABTDC*

Figure 14 presents the combustion course in the combustion chamber when the IAA was too big (Vp=28%, d=3 mm, $\varphi_{IAA}=45^0$ CABTDC). The combustion in the prechamber starts when the piston is far from TDC. After about 3 ms the pressure difference between prechamber and main combustion chamber is enough high and starts outflow from the prechamber through the clearance between partition and piston crown. However, the piston moves in the TDC direction and closes the clearance, then the stream begins to outflow through the nozzle hole in the partition. However stream energy is too small, because part of the mixture outflowed through clearance. The stream velocity, at short time after outflowing through the hole is reduced and the burning velocity has the value similar as in standard combustion chamber. After about 4.8 ms from combustion start, the stream displaces about 72% length of combustion chamber. These examples show that the selection of the IAA in the SOCC system is the most important.

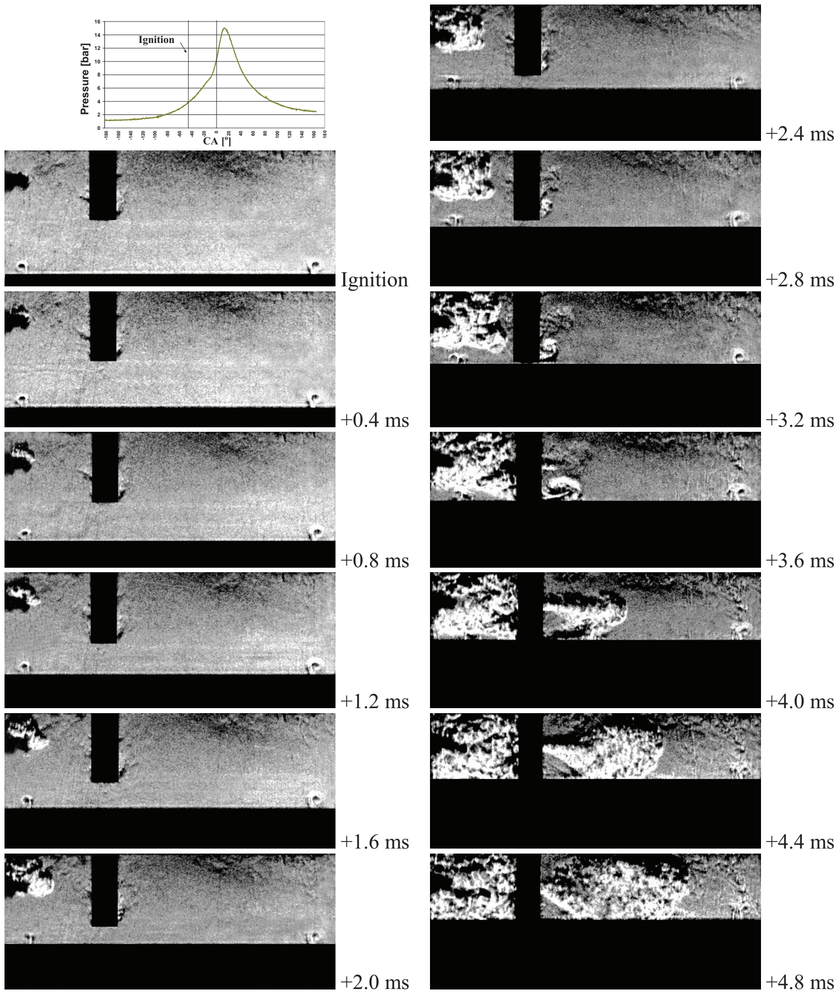



*Fig. 14. Combustion process development for too big of the ignition advance angle: $V_p$=28%, d=3 mm, ignition at wall, $\varphi_{IAA}=45^0$ CABTDC*

## 4. Conclusions

1. To obtain the best effects from applying the combustion system with semi-open combustion chamber for spark ignition engines, it need to preserve the assumed combustion mechanism in this system; the combustion process in the prechamber must be start in such moment, to assure that the pressure difference between prechamber and main combustion chamber attains relevant level, allowing on the outflow of the burned mixture and radicals stream from prechamber to main combustion chamber, when the piston is at TDC. Moreover, the stream energy, outflowing from prechamber to main combustion chamber, through orifice hole in the partition, must be so big to traverse all main combustion chamber, before the clearance between partition and piston crown will open.
2. The operation of the combustion system with semi-open combustion chamber is influenced first of all, by: design parameters – the volume rate of prechamber to full volume of combustion chambers, the dimension proportions of combustion chamber, the diameter (or diameters) of the orifice hole in the partition, the localization of the ignition place in the

prechamber and operation parameters – the ignition advance angles and the surrounding conditions. Among these parameters only ignition advance angles (IAA) may be continuously varied during the engine operation.

3. Lack of the linear dependences between the IAA and the engine performances for different engine speed and load is the most troubles concerning of the choosing of the relevant values of the system parameters.
4. To obtain the highest combustion efficiency and the best performances, the combustion in prechamber and main combustion chamber should be turbulent, because this means the cut short combustion time.
5. The prechamber volume (in rate to full combustion chambers volume) decides about the combustion time which is need to achieve the relevant pressure difference between pressure in prechamber and main combustion chamber and sufficient energy of the stream which outflow from prechamber to main combustion chamber. Therefore, if the prechamber volume is small, the combustion time is short but the stream energy is not enough to displace all main combustion chamber.
6. Because the best performances of the combustion system are obtained when the biggest stream range is achieved, the more profitable is when the main combustion chamber is short.
7. The orifice hole diameter decides about the stream flow resistance, so, first of all about the outflow start from prechamber to main combustion chamber, and velocity and range of the stream in main combustion chamber.
8. Localization of the ignition place influences first of all on the combustion character in the prechamber (turbulent or laminar) and it transposes at simple manner on the burning time in the prechamber until to outflow of the stream to main combustion chamber.
9. Because of that ignition advance angle is only one from the system parameters, which may be varied during engine operations, the map of IAA must be determined very precisely during time consuming and strenuous tests at the test stand, for many engine operation parameters. The determined of IAA values must be programmed in electronic control unit, which will be used during operation of the production engines.
10. To keep the assumed combustion mechanism in the system with semi-open combustion chamber the fuel/air composition must be hold on the precisely determined level, because the mixture composition has essential influence on the combustion velocity and time.

## 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] Gmurczyk, G. W., Leżański, T., Kesler, M., Chomiak, T., Rychter, T., Wolański, P.*, Single Compression Study of a Pulsed Jet Combustion (PJC),* 24$^{th}$ Symposium (International) on Combustion, The Combustion Institute, pp. 1441-1448, 1992.

[3] Jankowska-Siemińska, B., Jankowski, A., Slezak, M., *Analysis end reserch 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.

[4] 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.

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

[6] 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.

[7] 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, Vol. 9, No. 3-4, pp. 333-356, 2002.

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

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

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

[11] Jankowski A.*, Badania wpływu ziarnistości utleniacza na spalanie erozyjne paliw złożonych*, Archiwum Procesów Spalania, Vol. 1, No. 2, pp. 147-163, 1970.

[12] Jankowski, A., Seczyk, J., Wolański, P., *Badania rozpylenia paliwa za pomocą wtryskiwacza ze wspomaganiem powietrznym w komorze o stałej objętości*, International Scientific Conference on Combustion Engines KONES, pp. 593-598, Gdańsk 1993.

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

[14] 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.

[15] 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.

[16] 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.

[17] 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.

[18] 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.

[19] 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.

[20] Leżański, T., Sęczyk, J., Wolański, P., *Efekty zastosowania nowego systemu spalania w produkcyjnym silniku tłokowym o zapłonie iskrowym,* Combustion Engines – Silniki Spalinowe, No. 3, PTNSS-2011-SC-021, 2011.

[21] 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.

[22] Leżański, T., Sęczyk, J., Wolański, P., *Flame Front Propagation in Combustion System with Semi-open Combustion Chamber with Different Compression Ratio,* Journal of KONES Powertrain and Transport, Vol. 20, No. 4, pp. 227-235, Warsaw 2012.

[23] Rychter, T., Teodorczyk, A.*, An evaluation of effectiveness of the combustion jet in dual chamber configuration,* Archivum Combustionis, Vol. 4, No. 3, pp. 255-266, 1984.

[24] Jankowski, A., *Chosen Problems of Combustion Processes of Advanced Combustion Engine,* Journal of KONES Powertrain and Transport, Vol. 20, No. 3 2013, pp. 203-208, 2013.

[25] Jankowski, A., *Study of the influence of pressure, speed and type of gas stream on the combustion process, S*cientific Papers of the Air Force Institute of Technology, Issue 28, (in Polish) Warsaw 2010.