SOME PROBLEMS OF COMBUSTION SYSTEM OPERATION WITH SEMI-OPEN COMBUSTION CHAMBER FOR SPARK IGNITION ENGINE

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Abstract

The some problems concern of the new combustion system operation with semi open combustion chamber, which can be used in spark ignitions internal combustion engines are presented in this paper. These considerations are based on the visualization research results, with using rapid compression machine (RCM). In this researched combustion system the original combustion chamber was divided by partition in prechamber and main combustion chamber. This division of the original combustion chamber exists only when the piston is close to TDC, for the rest of the cycle the chambers are fully open. Ignition is initiated in the prechamber using electric spark plug, but the mixture in main combustion chamber is ignited by the stream of the burned gases injected from prechamber through the orifice in partition, if the ignition advance angle is correct. If the ignition advance angle is incorrect the mixture from prechamber will be outflowing through the orifice in partition and through the slot which is created between the partition and piston crowns. This last stream is swirled on the partition edge, what causes decrease of the stream speed outflowed from the orifice in partition to main combustion chamber. If the ignition advance angle is too big, then a peak pressure and compression work is very big because the burned gases are compressed instead of the fresh air/fuel mixture. This causes that the effective work is small and combustion efficiency is small.

Keywords: *SI engine, rapid compression machine, combustion, combustion process visualization, ignition advance angle*

1. Introduction

Manufactured at present modern piston SI engines apply almost exclusively two mixture preparation and combustion systems. The system with the fuel injection to intake port (PFI - Port Fuel Injection) and gasoline direct injection to the combustion chamber (GDI - Gasoline Direct Injection). The system PFI is less complicated operates in the all range with the stoichiometric fuel/air mixture, what makes possible the use of three-functional (TWC - Three Way Catalyst) catalysts to the utilization of exhaust gases. The GDI system with which one bound very large hopes on solution of all, or most of problems, concerning the fuel consumption and exhaust emission of internal combustion engines, is a system very complex. Especially complicated in the GDI are the fuelling and control systems, because when the mode operation is changed, (load and engine speed) follows the change of the operation mechanism of the systems. It turned out also that on the exit from the engine it could not obtain of the exhaust emission level which is required through legislative regulations. So necessary is the use of the catalytic aftertreatment system of the exhaust gases. Up to now did not work out the reliable catalytic system which, at the high durability, would be able to utilize effectively lean mixture of GDI engine, assuring the emission level on the exit from the exhaust pipe, to the level required through regulations. This is caused first of all because the engines GDI operated in the considerable map of characteristics, on the part load and lean charge. The aftertreatment of exhaust emissions in GDI engines, to meet of requirements entail the increase of the fuel consumption, so attained advantages become more and more smaller and he is more and more reasons, to seek simpler solutions , but assuring the fulfilment of obligatory levels of requirements.

Among such less complicated solutions which would be able to be competitive to the GDI and PFI engines, there is the combustion system with the semi-open combustion chamber which was worked out in the Department of Aeroengines of the Warsaw University of Technology. The researches use many research and development devices shown the positive results concerning fuel consumptions and exhaust emissions. These researches, which were conducted, using the rapid compression machine (RCM), let on the enough good recognition of the combustion mechanism. This let on programming and the execution of engine research, though in the somewhat limited range. In these researches was obtained results, in compliance with expectations.

The new combustion system was described in several publications [4, 5, 6, 7]. In this combustion system, the standard combustion chamber of the SI engine was divided on the prechamber and main combustion chamber, introducing the partition. There is one or more orifices in the partition. The prechamber has a volume several times smaller than the main combustion chamber. Both chambers are supplied with that some mixture of fuel-air. Ignition executes in the prechamber, using of the electric spark plug. When the pressure difference between the prechamber and the main combustion chamber reaches the suitable level, then follows the outflow of burning mixtures and radicals, from the prechamber to main combustion chamber, which causes the ignition of the mixture in the main combustion chamber. At the suitable configuration of research parameters the speed of the stream displacement outflowed from the prechamber to the main combustion chamber can be greater from the speed of the free combustion. So then follows the shortening of the combustion process time, together in the prechamber and main combustion chamber. In effect it can obtain the greater efficiency of the combustion and the smaller exhaust emission of the engine. The obtainment of positive effects requires however the selection of profitable parameters of research, as: the proportion of the volume of the prechamber to main combustion chamber, the orifice diameter in the partition separating the prechamber from main combustion chamber, the ignition place and the ignition timing. Among these parameters only the ignition timing can be varied in the continuous manner during the engine operations, without of the engine disassembling. Therefore values of individual parameters should be selected in versatile researches, and to these remaining parameters should be chosen the optimum advance angle.

The engine researches with the use of the apparatus to measurement of the high-speed changed parameters of research permits to evaluate effects of introduced changes of parameters, but the mechanism which is responsible for these effects can be only guess. Therefore best effects, concerning explanations of the mechanism, is reached exploring of process visualization using RCM. On obtained photographs of the combustion it can analyzes the course of the combustion process and evaluate the influence of changes in research parameters during the combustion course.

2 Design description and research method

The aim of proposed design was: reduction of fuel consumption, decrease of exhaust emissions and ignition improvement. The idea of solution was derived from working cycle analyses of compression-ignition engines with divided combustion chamber and SI engines with prechamber. In these engines the repeatable and reliable ignition, the low exhaust emission, uniform and smooth operation, smaller noise is gained, though with the somewhat greater fuel consumption. Obtained effects are caused a better process mixture preparation and a repeatable ignition. However the use of divided chambers complicates a engine design and the enlargement of the fuel consumption is caused by necessity of overcoming of additional resistances in internal flows. To avoid these losses is proposed the solution in which the division on the prechamber and main combustion chamber appears only at the time, when the piston is near TDC (in the range ± 10º CAD with relation to TDC).

In the remaining part of the cycle the combustion chamber operates as the open chamber so drag losses should be minimum and because it can be obtained the higher combustion efficiency this one should also allows to obtain positive effects concerning fuel consumptions. Recognition of the combustion mechanism in the system, with divided combustion chamber, has the key-meaning for the obtainment of the best effects in the engine operation. It enables the best selection of design parameters. The best method of research, for the recognition of the mechanism of the combustion, is the visualization method. The elaboration was based on visualization researches realized on the test stand, with the utilization RCM, shown on fig. 1.

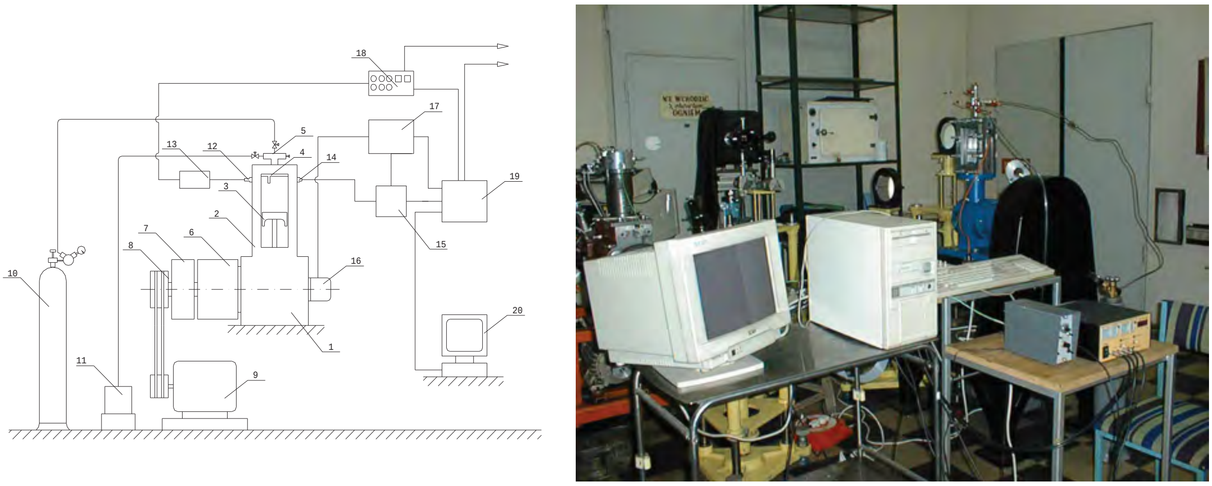

Fig. 1. Schematic and view of RCM test stand
1. Crank mechanism, 2. combustion chamber, 3. piston, 4. insert model combustion chamber, 5. Refuelling and emptying system, 6. electromagnetic clutch, 7. flywheel, 8. external belt transmission, 9. electric motor, 10. pressurized bottle, 11. vacuum pump, 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

The details concerning of the test stand design, RCM, and the leadings research methods can be find in [5, 7]. The research results at the form of the photographs of the course of the combustion, and the course of the pressure in the combustion chamber ware obtained during research. The most essential parameters of the combustion process in this system are: the proportion of the volume of the prechamber to the volume sum of the prechamber and main combustion chamber, the orifice diameter in the partition, the ignition place and the ignition timing. At this system the ignition timing is the only parameter which can be varied during the work of the engine. Changes of remaining parameters require the disassembly of the engine. That's why investigations were conducted in such manner that the configuration of three parameters (the prechamber volume, the orifice diameter in the partition, the ignition place) had to fixed and then the ignition timing was changed over wide range values. At every change of system parameters the course of combustion was registered using photographic drum-camera. Thanks to this it could observed not only as changes of individual parameters influence on performance data of the engine, but also which phenomena cause these changes. It found out that only at the strictly determined system configuration, under the engine operation conditions, were obtain positive effects. The modification of the engine work conditions requires the change of the system configuration, in this case the ignition timing. Remaining parameters of the system are selected in such manner, so that they able to accommodate to requirements at all working conditions of the engine operations. The correct value of the ignition timing should be chosen in such manner, so that the outflow of the stream of burning mixtures from the prechamber to main combustion chamber follow then, when the piston is at TDC. Then the outflow of the stream of burning mixture from the prechamber to main combustion chamber takes place through the orifice in the partition. The stream will has the greatest energy and at high speed will displace through the main combustion chamber, and from it flame front will ignites following layers of the mixture contained in the main chamber.

3. Role of the swirl forming on the edge partition

If the ignition timing is not selected correctly, then the outflow of the burning gases stream from the prechamber to main combustion chamber will take place, both through the orifice in the partition, and through the slot between the partition and the piston crown. The proportion between the quantity of gases outflowed through the orifice and slot is relative to values of the ignition advance angle, because this depends on the slot section field. From this proportion of outflowed gases depends the speed of combustion in the both combustion chamber and attained effects, as decrease of the mixture combustion time, what was illustrated on the photographs. On fig. 2 the course of the combustion in the following system configuration is shown: prechamber volume - 10% sums of the volume of the prechamber and main combustion chamber, orifice diameter in the partition - 3 mm, ignition place - the centre of the prechamber, ignition timing - 20º CAD before TDC. On fig. 2 it is visible that the flame front in prechamber, after the ignition, spreads on the spherical surface. When the piston is near TDC follows the outflow of the burning stream from the prechamber to main combustion chamber. However the stream has too small energy, to traverse the main combustion chamber quickly.

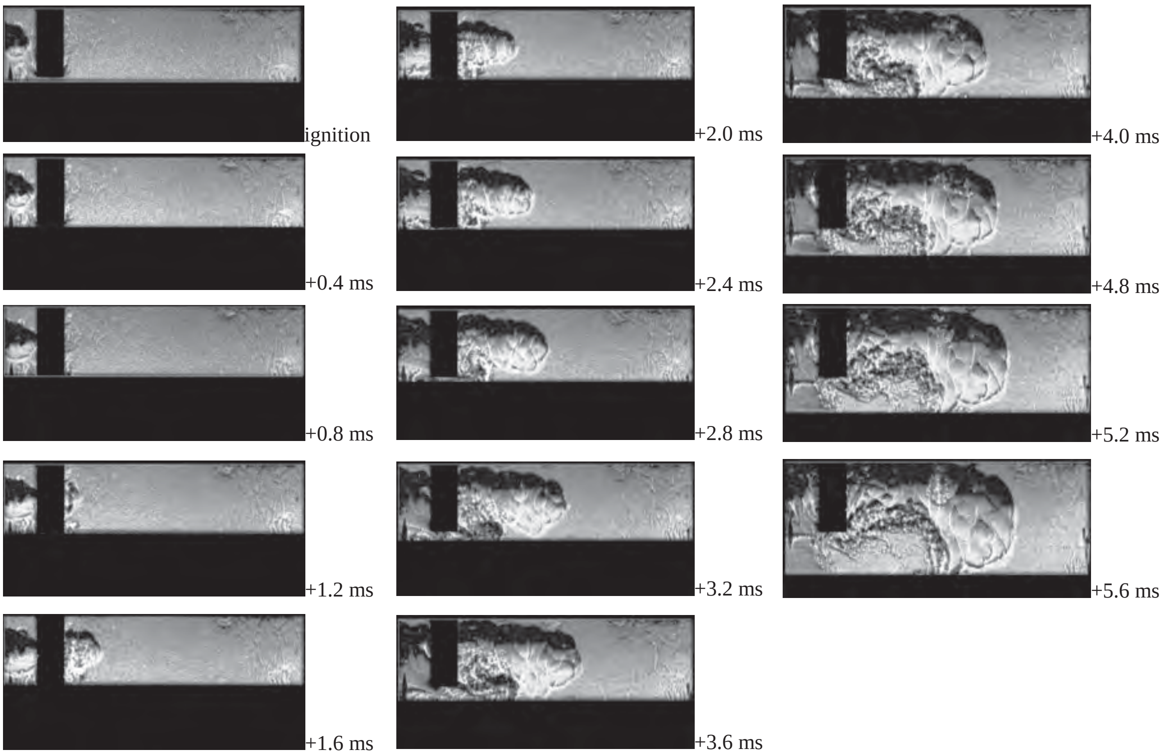

Fig. 2. Course of combustion in RCM for system configuration: V_{kw}=10%, d=3mm, ignition in the prechamber centre, φ_{wz}= 20º CAD BTDC

Therefore when the crankshaft will turn approx. 10º CAD and it causes the exposure of the large slot between the partition and the piston crown then burning the mixture will begin to outflow through the slot (not only through the orifice in the partition). When the stream flows through the slot, then it cause that the stream experiences swirling at the partition edge what is visible on fig. 2. The direction of the swirl rotation is opposite to the direction of the stream outflowed from orifice in the partition. This causes that the speed of stream displacement through the main combustion chamber will decreases distinctly. The graph of stream displacement through the main combustion chamber on the fig. 3 is shown.

It is visible that when follows the outflow of the stream through the slot between the partition and the piston crown, approx. 2.4 ms since the ignition, follows the distinct decrease stream velocity through the main combustion chamber, and the speed of the stream displacement through the main combustion chamber approaches the speed of displacement of the flame front in the standard chamber, what bear witness about the lack of the combustion process acceleration. As far as directly after outflowing of the stream, from the prechamber through the orifice in the partition, it has a speed about 17.25 m/s, this after the outflow of the second stream through the slot, the speed of the combustion attains the value 4.75 m/s only, so is about four times smaller.

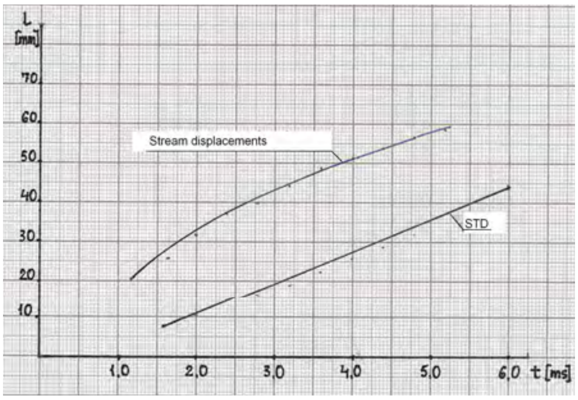

Fig. 3. Flame front travel versus time for the situation presented on fig. 2

The variation of the combustion speed is caused also this that small is the prechamber volume, with relation to the total combustion chamber volume. So the quantity of the burnt mixture in the prechamber is small, and the high value of pressure difference at the beginning outflow between the prechamber and main combustion chamber drops quickly.

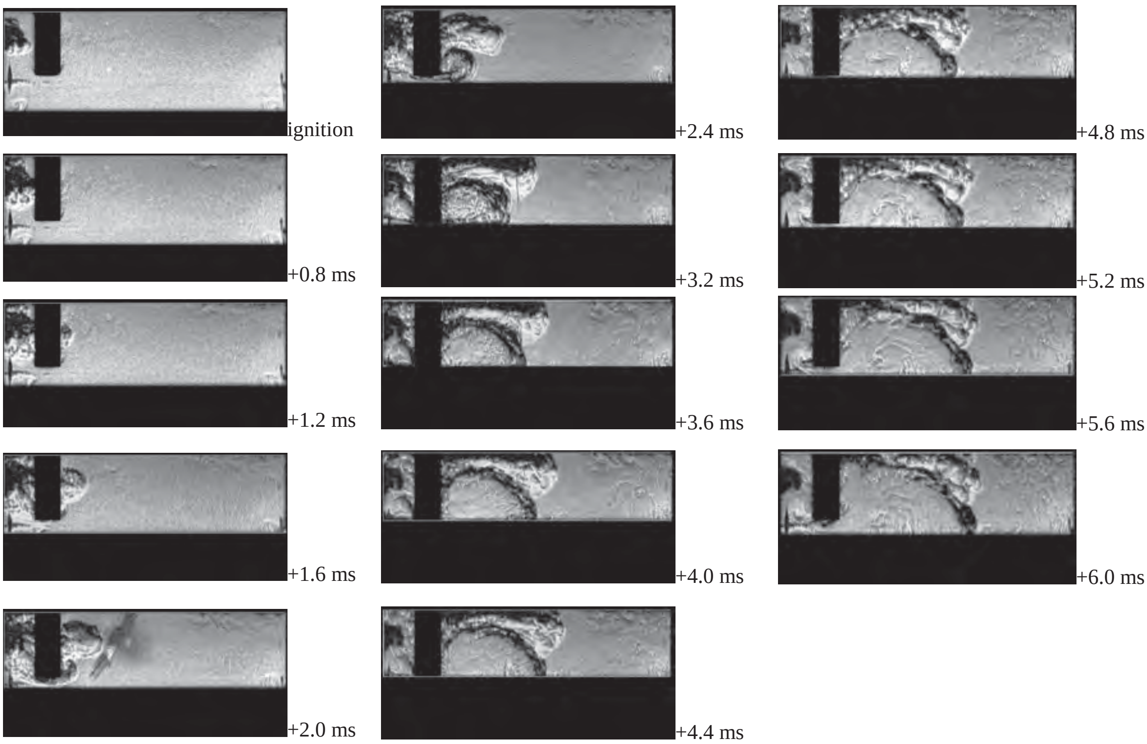

Fig. 4. Course of combustion in RCM for system configuration: V_{kw}=10%, d=3mm, ignition in the prechamber centre, φ_{wz}= 50º CAD BTDC

On fig. 4 the course of the combustion in the system with following parameters are shown: the prechamber volume - 10% orifice diameter - 3 mm, ignition in the prechamber centre, ignition timing - 50º CAD before TDC. The burning expansion in the prechamber, after the ignition, had a similar character, as on fig. 2. Because however the big ignition timing was applied then the outflow of burning streams from the prechamber to main combustion chamber will follow already before the piston approaches TDC and it closure slot between the partition and the piston crown. There appeared the outflow of burning mixtures both through the orifice in the partition, as well through the slot. The stream outflowed through the orifice in the partition had at beginning greater speed, but the swirl is appear, with the turns direction opposite to displacement of the stream outflowed through the orifice, causing the deceleration of the flow, and more and more dominant parts began to perform swirling. The stream outflow by the orifice was pressed to the surface of the cylinder head, what caused still greater braking of the speed of displacement and after time 4.4 ms both streams shifted already with the similar speed. In the moment when the piston achieves the TDC, the slot between the partition and a piston crown was closed and still the stream outflow speed through the orifice was greater, than outflowed through the slot. Re-opening slot after passing TDC caused the distinct enlargement of the speed of displacement of swirling and after about 5.6 ms this speed was already greater.

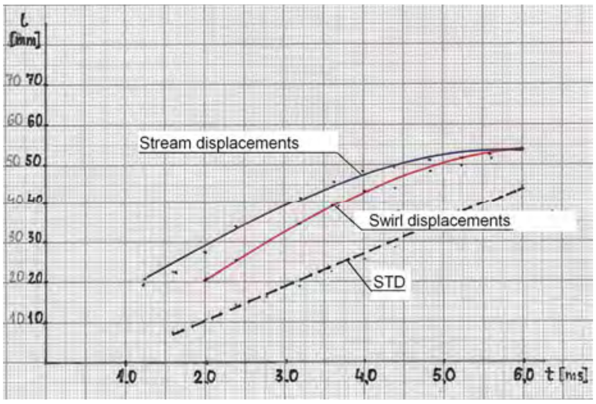

Fig. 5. Flame front travel versus time for the situation presented on Fig. 4

The graph of stream displacements versus time through the main combustion chamber was shown on fig. 5. It is visible, that the swirl appearance on the edge partitions causes the distinct deceleration of the stream displacement outflowed through the orifice in the partition and then the speed of these displacement is closer and closer to the speed of the flame front in the standard chamber.

Results introduced on above-drawings and graphs show how essential is the proper selection of the ignition advance angle before TDC. The incorrectly selected ignition advance angle causes the appearance of the outflow through the slot between the piston crown and the partition, appearance of the swirl on the edge partition and in effect the deceleration of the combustion, what is aim of proposed solution.

4 Influence of ignition timing on pressure

The proper selection of the ignition timing has also an essential influence on the obtainment of the highest effective work and high combustion efficiency. On fig. 6 it was compared the pressure in the combustion chamber histories versus of the crank angle degree (CAD) for the following system configuration: the volume of the prechamber - 10% orifice diameter in the partition - 3mm, ignition place - the centre of the prechamber, for three different values of the ignition timing: 20º CAD, 30º CAD and 50º CAD. Comparing graphs can be noticed that the least compression work was obtained in case of the ignition timing 20º and 30º CAD. The higher compression work was obtained at the greatest ignition timing 50º CAD before TDC. This is caused this that in case of the ignition timing 20º and 30º CAD before TDC to tensing was subject of the fresh mixture in the main combustion chamber and the burning mixture in the prechamber, but in case of the ignition advance angle 50º CAD before TDC a combustion was seized already the bulky volume of the main combustion chamber and this mixture - the fresh mixture and burning gases mixture it was subjected to compression.

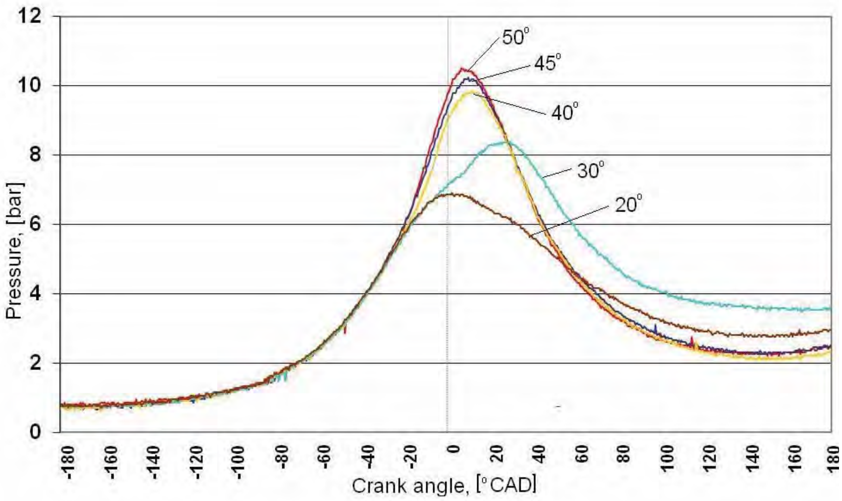

Fig. 6. Comparison of pressure courses in RCM combustion chamber for different ignition advance angles: 20º CAD, 30º CAD, 50º CAD BTDC (System configuration V_{kw}=10%, d=3 mm, ignition in prechamber centre)

Indeed in case of the ignition advance angle 50º CAD before TDC the highest maximum pressure value is obtained, but this was caused a necessity of compression of burning mixtures and it did not obtain from this reason of the effective work enlargement. The greatest effective work was obtained in case of the ignition timing 30º CAD, however these values in case of the ignition advance angle 20º and 50º CAD were similar despite essential differences in the maximum pressure values (for φ_{wz}=20º CAD 6.9 bar; for φ_{wz}= 30º CAD 8.4 bar; for φ_{wz}= 50º CAD 10.6 bar). The compression work and the effective work for above mentioned of the ignition timing values on fig. 7 was compared. As far as differences in the compression work were about 10%, then in the effective work exceeded 40%, what bear witness to the very crucial role of the swirl which appears with the inadequate selection of the ignition timing.

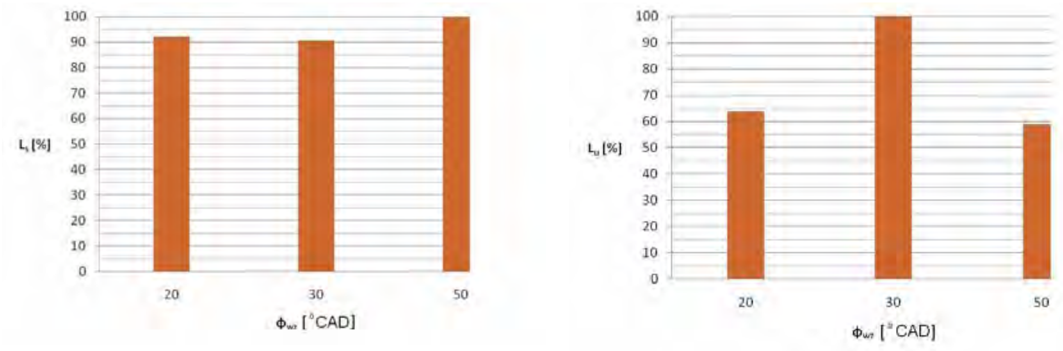

Fig. 7. Comparison of compression work (L_s) and effective work (L_u) of RCM for ignition advance angle: 20º CAD, 30º CAD, 50º CAD BTDC (System configuration V_{kw}=10%, d=3 mm, ignition in prechamber centre)

5. Summary

In represented work operation the new combustion system from point of view of influence of the ignition advance angle on the course of the combustion, the maximum pressure in the cycle, the compression work value, and the effective work was analyzed. It was stated the crucial role of the swirl, which forms itself on the partition edge, during the outflow of the stream from the prechamber through the slot between the partition and the piston crown, instead of through the orifice in the partition, if the selected ignition timing is incorrect. This swirl causes the distinct decrease of the stream displacement speed, outflowed from the prechamber to main combustion chamber, through the orifice in the partition. In the extreme case the all stream from the prechamber to the main combustion chamber can flow out through the slot, what can take place if the ignition timing will be very small.

The incorrectly selected value of the ignition timing can be also a reason of the compression work increases and the big maximum pressure in the cycle. This high pressure value will not causes that the large effective work will be achieved. If the large values of the ignition timing are applied, only the burning gases are compressed instead of the fresh mixture. This mixture has high specific values.

The research results show that elaborated system is sensitive in relation to the ignition timing and therefore its using in the working engine will require the elaboration of the special control system which will be change the ignition timing depending on working conditions of the engine (first of all the engine speed and the engine load). This is especially important in case of traction engines working on the wide range of engine speed and loads.

6. References

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