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INERTIA-DRIVEN SINGLE COMPRESSION MACHINE FOR COMBUSTION STUDY

The paper presents an original design of a single compression machine for combustion study. The principle of operation is based an old concept, utilizing the inertia energy of a flywheel to accelerate the crank mechanism and the attached piston to compress rapidly the combustible mixture in the combustion chamber. A square piston geometry was adopted to allow visualization of the compression and combustion processes in directions perpendicular to the cylinder axis. To avoid the extensive scratching of glass walls by the moving piston, a special multi-action clutch-brake unit was used; this facilitates coupling of the flywheel with the crank mechanism during the single piston stroke and subsequent immediate uncoupling and fast stopping of the piston. The whole operating cycle can be completed within no more than two revolutions of the crankshaft. The design details of the machine, its acceleration characteristics and a sample of the visualized combustion process are presented.

1. Introduction

Single compression machines (SCM) are known as a very useful tool for combustion studies in the systems where the combustion mixture is ignited at elevated pressure. The situation like that is typical for internal combustion piston engines. The general reason to use the model experimental setup instead of an actual engine in these cases is the need to visualize the combustion processes in the combustion chamber, which would be very difficult or impossible to achieve in the real engine. A variety of solutions of research engines equipped with optical access are documented in the literature. Most of them offer the optical access in the direction along the cylinder axis and they are

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called, depending on the design details, the transparent piston or/and transparent cylinder head engines [1], [2], [3], [4]. In that type of the engine, the mechanical contact of the moving parts with the glass windows does not take place, and therefore there is no danger to scratch the glass. This type of research engine does not allow for the visualization of the combustion processes in the direction perpendicular to the cylinder axis. To achieve optical access to the combustion chamber in that direction, it is inconvenient to have the flat cylinder wall or – when using the schlieren system – two walls parallel to each other. In other words, the engine like that requires square or rectangular piston geometry. The construction of that type of the engine is possible, and it was proved in practice [5], [6], [7]. The difficulties associated with the construction of such an engine are, however, significant, and the parameters of the combustion system depart remarkably from the engine reality. For this reason, that type of the research engine design does not seem to be a very popular research tool.

The single compression machine designed to visualize the in-cylinder processes in the direction perpendicular to the cylinder axis appears to be a more useful research tool in some cases, because of simpler construction, and especially – because it eliminates of the difficulties created by the high temperature level existing in the operating engine. That type of the research tool cannot substitute the engine, but it is closer to the engine reality than the constant volume bomb, because it is able to simulate the part of the engine cycle composed of both: compression and expansion strokes. Although the square or rectangular piston geometry is not realistic either, it makes it possible to investigate the in-cylinder gas motion, which would be difficult to observe in the direction along the cylinder axis (for instance – the squish effect).

2. General idea

2.1. Basic assumptions

The single compression machine with the optical access perpendicular to the cylinder axis (designed for the use of the schlieren technique) has to satisfy the following major requirements. It has to:

- be able to simulate compression and expansion strokes of the piston;
- reduce as much as possible the number of crankshaft revolutions before the compression stroke and after the expansion stroke;
- accelerate piston as much as possible to achieve the required compression pressure;
- avoid the machine vibrations within the range of frequencies which would influence the quality of photographs.

It has been considered that the best, and at the same time realistic assumptions would be:.

- to start piston motion around the bottom dead center of the crank mechanism and to achieve the piston speed at the end of the compression stroke comparable with that of the actual engine at assumed engine speed;
- to stop the piston motion within the 180 deg after the end of the expansion stroke;
- to attain the compression pressure on the level at least 0.6 MPa.

2.2. General layout

The general layout of the SCM test rig is shown in figure 1. The rig consists of the following major units and sections: the driving unit (1), the electromagnetic clutch-brake unit (2), the crank mechanism (3) and the research section (4). The shafts of the units 1, 2 and 3 are provided with ball bearings independently from each other and they are mechanically coupled to create the core of the single compression machine.

The driving unit consists of the flywheel coupled with the electric motor of the following parameters: power – 1.5 kW and the rotational speed – 1440 rpm. The suitable motor-to-flywheel speed ratio assures the rotational speed of the flywheel of 1850 rpm in this particular case. It can be easily changed by changing the diameters of the flexible wedge belt wheels.

The electromagnetic clutch-brake unit is a commercially available fast acting part of the milling machine. According to the required preset sequence of the electric impulses, the unit is first coupling the flywheel with the shaft of the research unit, then it is disconnecting them and is immediately activating the process of stopping (braking) of the crankshaft.

The crank mechanism section consists of the crankshaft, the slider, the piston rod and the rectangular piston which is reciprocating in the rectangular cylinder having the following dimensions: width 70 mm and depth – 30 mm. The piston stroke is 78 mm. The connecting rod length is 132 mm and the length of the piston rod – 180 mm. Although the cylinder and the piston in the presented design, are of the rectangular cross section they could be cylindrical as well. The cylindrical shape of the cylinder would not make it possible, however, to perform the visualization of the combustion process (without any correction techniques) except along the cylinder axis via transparent cylinder head.

3. Design and control details

3.1. Research section

The schematic of the visualization in the SCM research section is shown in figure 2. The front and back walls of the cylinder are made of glass and they allow for the visualization of all the phenomena which occur during the whole

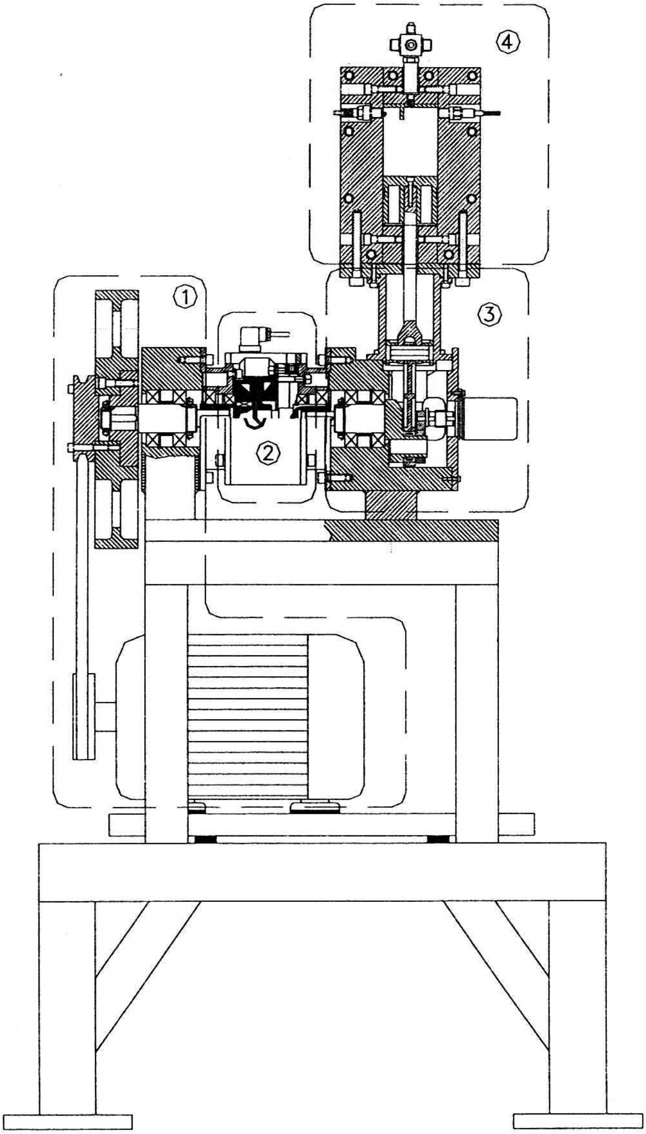

Fig. 1. General layout of the SCM: 1 – driving unit; 2 – electromagnetic clutch-brake unit; 3 – crank mechanism; 4 – research section

length of the compression and expansion strokes. The shape of the combustion chamber can be modified either by mounting a new cylinder head, or by introducing and fixing to the inner surface of the cylinder head (or to the piston crown) the insert shaped according to the particular needs. In the presented version, the insert designed to generate squish was used.

The design details of the research section of the SCM are presented in figure 3.

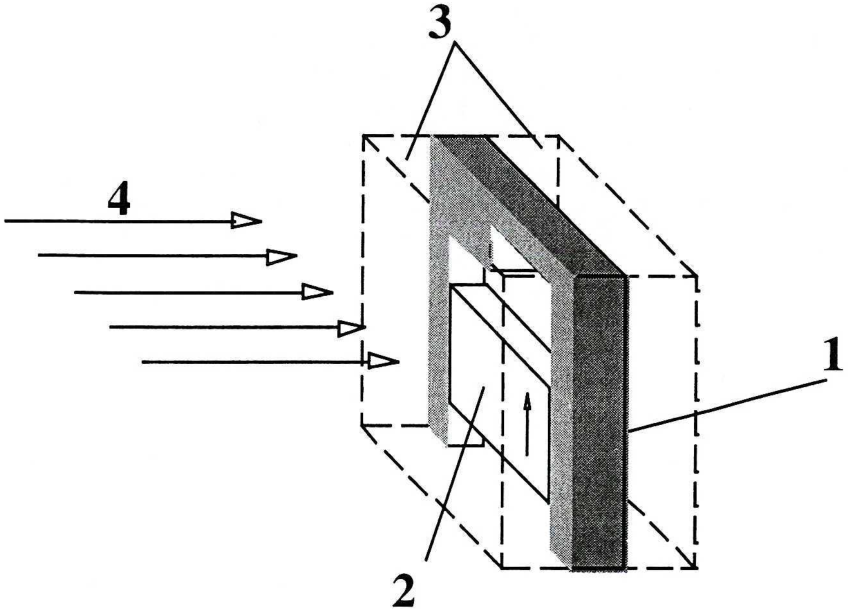

Fig. 2. Schematic of the visualization: 1 – cylinder walls; 2 – piston; 3 – glass walls; 4 – visualization direction

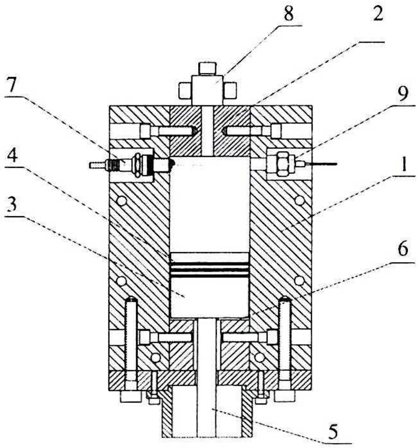

Fig. 3. Design details of the research section: 1 – side parts of the cylinder; 2 – top part of the cylinder; 3 – piston; 4 – piston seals; 5 – piston rod; 6 – piston bottom rubber gasket; 7 – spark plug; 8 – mixture feeding unit; 9 – pressure transducer

The crucial problem which had to be solved was to assure the required tightness of the piston in the cylinder. The set of three rows of piston seals was used, each of the rows being composed of four straight pieces of plastic strips which were interacting with each other at the cylinder corners. This solution made it possible to attain the required compression pressure of about 0.6 MPa but, unfortunately, slight leaks of the compressed medium through the sealing corners still were detected. This influenced a bit the shape of the registered pressure time diagrams, but one decided that it was acceptable from the point of view of the correctness of the conclusions drawn from the qualitative observations of the compression, combustion and expansion processes.

The cylinder of the machine has to be filled up with the flammable mixture before the machine starts up. At that stage of the machine preparation for the test, the piston is in its BDC position. To avoid any leaks of the mixture out of the cylinder during fill-up operation, an additional rubber sealing gasket is placed at the bottom surface of the cylinder. The bottom part of the piston is pressed against this rubber gasket preventing any leaks. Now, the cylinder is isolated from its surrounding, the gas from the cylinder can be evacuated with the use of the vacuum pump, and the cylinder can be filled up with the test mixture.

The presence of the conventional-like crank mechanism assures the kinematics and dynamics of the piston motion similar to that of the conventional reciprocating piston engine. All the moving parts of the machine were designed as light as it was possible. A compromise must be made between the weight of the moving parts and their strength and rigidity, as the parts are designed to stand significant inertia forces during the fast piston acceleration.

3.2. Control and measuring equipment

The electronic control unit, which the machine has been equipped with, controls all the preset system parameters, synchronizes whole sequence of the machine operation and the pressure pickup, and coordinates the picture taking procedure. The schematic of control and measuring equipment is shown in figure 4.

The voltage of 24V was supposed to be applied to activate the clutch-brake unit. This voltage was increased up to 32V to shorten the time of the clutch and the brake reaction which was about 20 ms eventually (*finally, this time was reduced to 20 ms*). This unit was able to transmit the torque of 60 Nm.

The computer control unit was designed to assure the following sequence of events: starting the piston motion, activating the spark ignition, starting and synchronizing the picture taking process, triggering the data acquisition system to register pressure profile, crankshaft speed etc., and assuring the proper time correlation of these events.

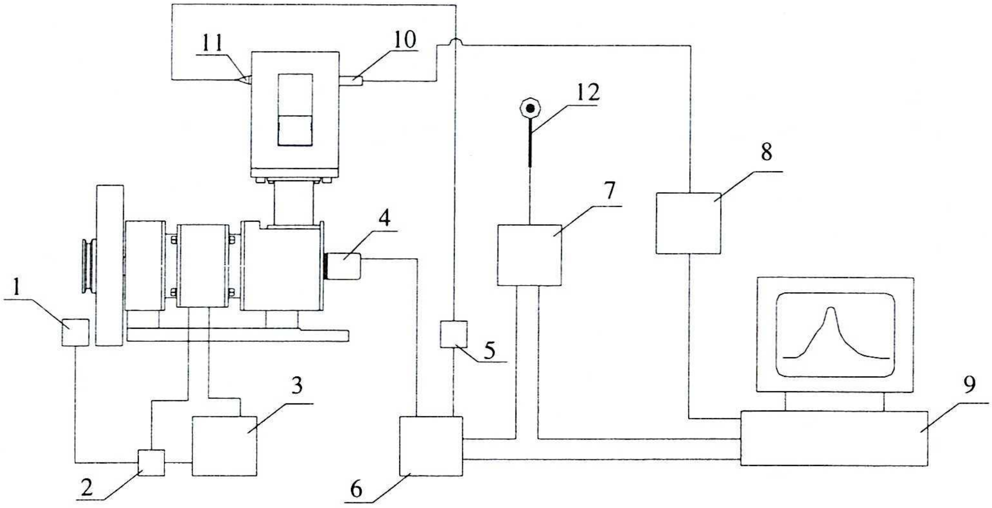

Fig. 4. Schematic of the control and measuring equipment: 1 – speed sensor; 2 and 3 – clutch-brake control units; 4 – crankshaft position marker; 5 – ignition unit; 6 and 7 – picture taking control unit; 8 – amplifier; 9 – data acquisition system; 10 – pressure transducer; 11 – spark plug; 12 – laser diode

4. Testing and calibration

Series of test runs were performed to check how much the dynamics of the machine piston motion is similar to that of the actual engine having the same dimensions of the crank mechanism. The crankshaft rotational speed (measured) increases gradually from zero at the BDC (-180 deg CA) up to 1770 rpm at the TDC, driven by the energy of inertia of the flywheel (Fig. 5). Around TDC the crankshaft speed stabilizes and remains constant.

The comparison between the measured and calculated (for the constant speed of 1770 rpm) piston velocity profiles are presented in figure 6. The differences between them are remarkable during the start-up period (from 180 to 0 deg CA) but starting from the TDC piston position they are basically the same. Slight differences result from the fact that the calculated profiles concern only the crank mechanism itself and they do not take into account the effects of the pressure changes in the cylinder (during the machine cold operation) while the measured profiles do. The increasing speed of the machine crankshaft (from zero) results in the decrease of maximum velocity of the machine piston during the compression stroke by about 33% but for the expansion stroke the velocity profiles: measured and calculated are practically the same. Also the piston maximum acceleration (Fig. 7) is lower during the compression stroke than it would be in the case of the constant speed of the engine. Some minor disturbances, which appear on the experimental curve, result from the amplified (second derivatives) measurement "noise" during the detection of the piston motion. During the expansion stroke, the piston acceleration profiles are similar for both cases except that for the machine the profiles around their maxima are slightly disturbed by the above – mentioned fluctuations of the crankshaft speed.

For the researcher, the most interesting processes to investigate usually take place within about 30 deg before TDC and during the expansion stroke then it can be concluded that the dynamics of the machine piston motion can simulate the conditions in an actual engine with the satisfactory precision.

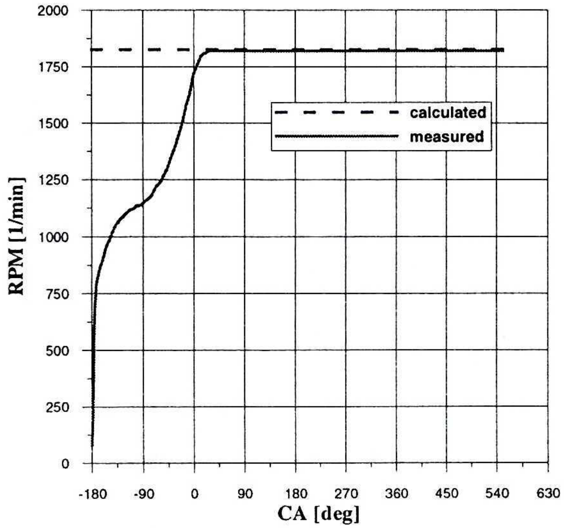

Fig. 5. Measured instantaneous rotational speed of the crankshaft vs. crank angle

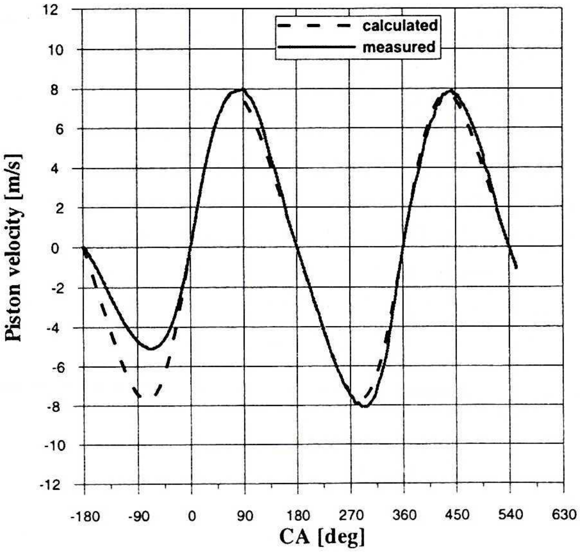

Fig. 6. Measured and calculated piston velocity profiles (at the 1770 rpm)

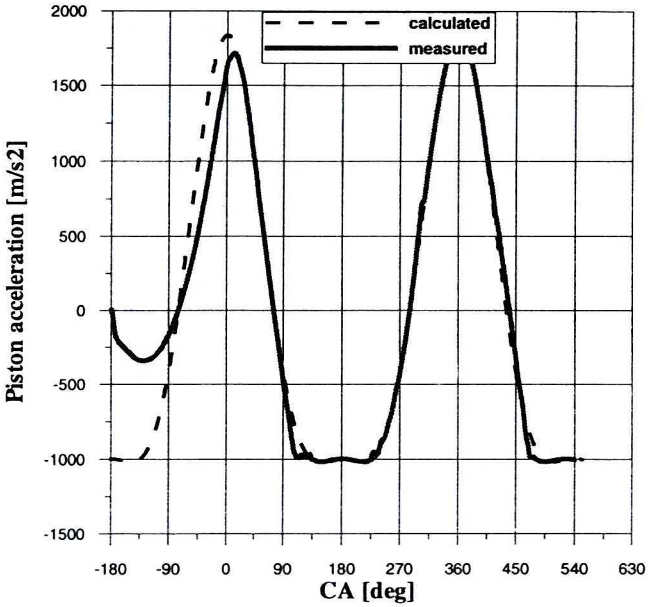

Fig. 7. Measured and calculated piston acceleration profiles (at the 1770 rpm)

The pressure profiles in the machine cylinder (cold operation) during the first two crankshaft revolutions are presented in Fig. 8. For the assumed compression ratio of 7.1 the maximum pressure registered during the first compression cycle was about 0.58 MPa. For the next compression cycle, the pressure was lower by about 20%, because of two reasons: leaks of the compressed gas through the piston seals and the cooling effect of the cold glass cylinder walls. This is also the reason for lowering the minimum pressure below starting (atmospheric) pressure after each consecutive cycle. Fortunately, due to the fast piston acceleration, all the measurements can be done during the first compression-expansion cycle of the machine.

5. Visualization

The major function of that type of the SCM is the visualization of the in-cylinder processes during the compression and expansion stroke of the piston. As it was specified above, the machine design should make it possible to avoid the machine vibrations within the range of frequencies which would influence the quality of photographs. This condition was fully satisfied and the proof of that is presented in figure 9. The series of framed pictures shown there are taken in the direction perpendicular to the cylinder axis. The geometry of the combustion chamber was design to generate the effect of the squish in the time when the piston approaches the TDC position. The spark advance angle was 40 deg BTDC. The subsequent development of the combustion process initiated by

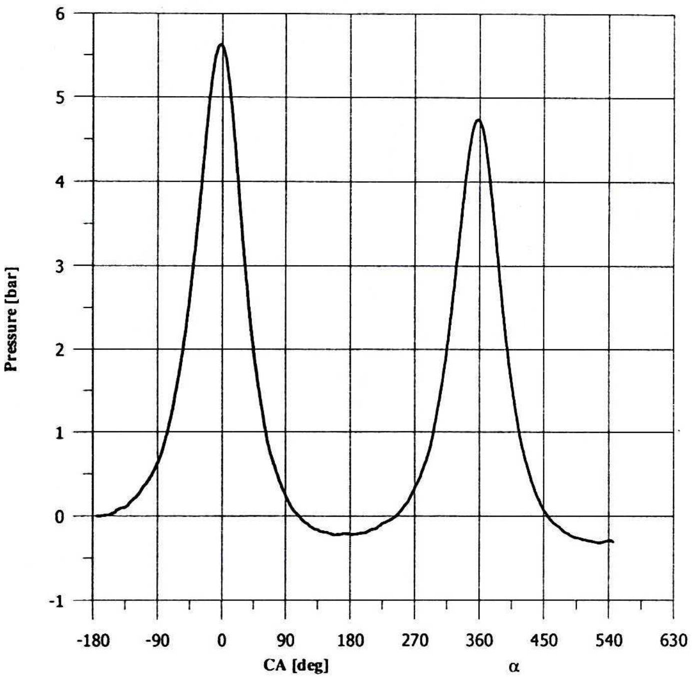

Fig. 8. Pressure profiles during first two crankshaft revolutions

the conventional spark plug located at the left side of the chamber was registered with the use of the schlieren optical system. The quality of these pictures seems to be quite satisfactory. Moreover, the behavior of the turbulent gas mixture (unburned) coming out of the squished area was also registered and is visible good quality in pictures despite the fact that the temperature of this gas was remarkably lower than that in the combustion zone.

6. Possible modifications

The SCM presented in this paper was designed to study the compression, combustion and expansion processes in spark ignition piston engines. The most original feature of this machine is its driving mechanism. The combination of the idea of using the inertia of the flywheel as a piston driving force and the application of the fast acting electromagnetic clutch-brake unit made it possible to accelerate the research piston to the required speed within the 180 deg of CA and to stop the piston motion within the next 360 deg CA. This type of the driving mechanism is universal and it can be applied to any research tool of the type of the SCM where the fast piston acceleration is required. The magnitude of the piston acceleration depends on the weight of the flywheel and the settings of the clutch-brake unit. All these parameters can be well controlled.

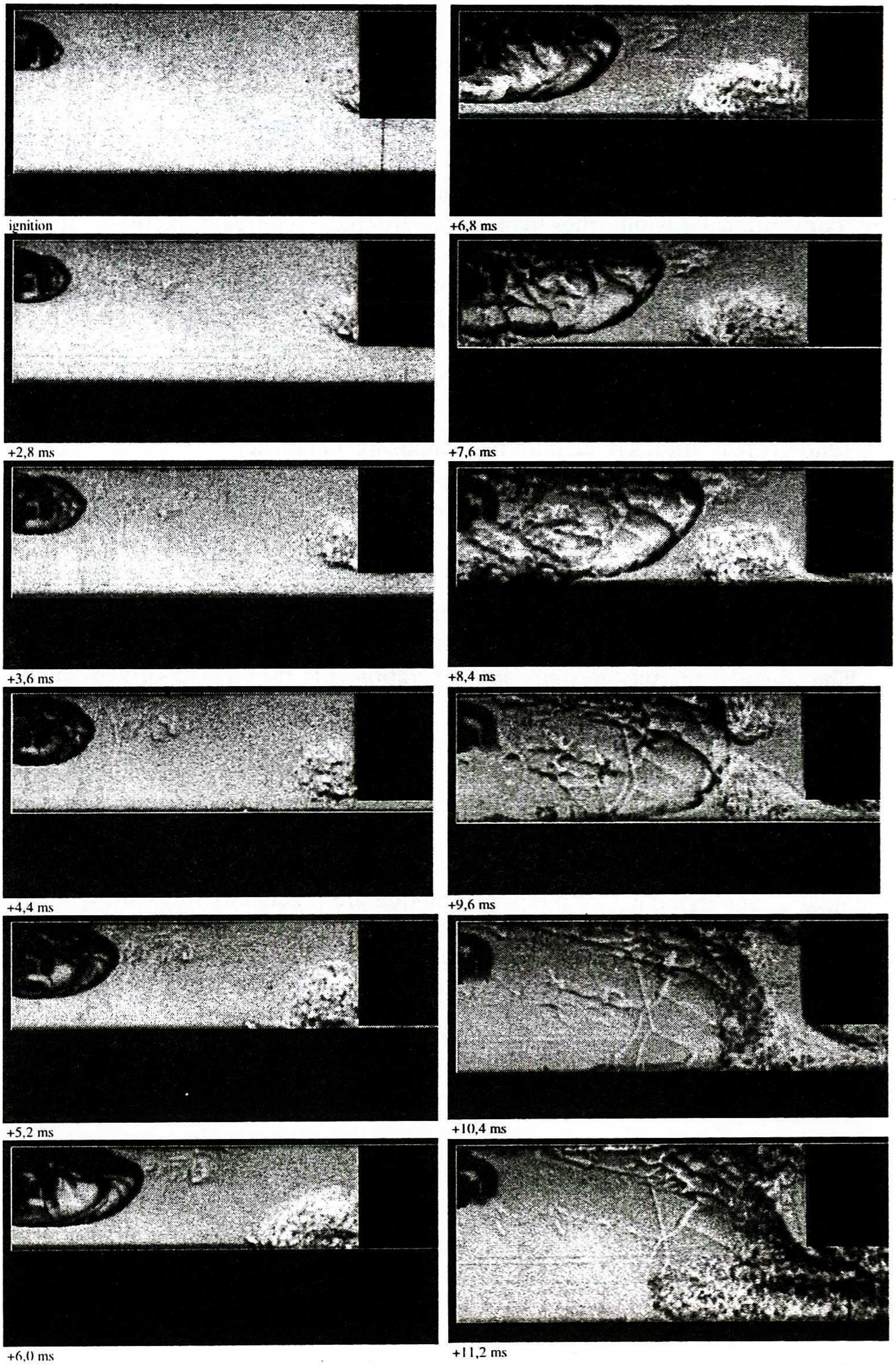

Fig. 9. Example of the series of the schlieren framed pictures of the combustion process in the "squish" geometry

The test section itself can be designed according to the particular research needs. It is possible, for instance, to use the test section with the conventional cylindrical piston equipped with the traditional piston rings. In this case, it would not be possible to visualize the combustion process in the direction perpendicular to the cylinder axis, but it is still possible to do it along the cylinder axis via the glass window in the cylinder head. Cylindrical piston and the conventional piston rings can allow for the significant increase of the compression ratio. The compression pressure in this case might be sufficiently high to initiate the spontaneous combustion, which would make it possible to investigate the combustion processes related to diesel engines. Of course, this type of a research would require some additional arrangements as – for instance – preheating of the air in the cylinder before starting the machine. The possibility to achieve the fast compression of the charge could also be used for the fundamental studies related to the combustion chemistry.

The mentioned short list of the possible applications of the general idea of the presented SCM indicates that this research tool has a potential to be quite universal.

7. Summary

The details of the design and operation of the inertia-driven single compression machine were described. The presented type of the driving mechanism is universal, and it can be applied for any research tool which has to assure fast compression and expansion strokes of the piston within the single revolution of the crankshaft. The presented arrangement of the test section of the SCM allows for visualization of the combustion process in the direction perpendicular to the cylinder axis with the required quality of the pictures. The kinematics and dynamics of the piston motion are practically the same as those of the actual piston engine running at assumed engine speed. The extensive research work which has been done so far with the use of the this SCM (which will be reported elsewhere) proves that it is an efficient tool for combustion study in the casws where the fast change of the combustion chamber volume is required.

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Bezwładnościowa maszyna pojedynczego sprężu do badań procesu spalania

Streszczenie

W artykule przedstawiono oryginalne rozwiązanie konstrukcyjne maszyny pojedynczego sprężu przeznaczonej do badań procesów spalania. Zasada działania maszyny jest konwencjonalna, natomiast do jej napędu wykorzystano bezwładność koła zamachowego, którego energia umożliwia szybkie przyspieszenie mechanizmu korbowego, niezbędne do sprężenia mieszanki palnej w komorze spalania. Użyto cylindra i tłoka o prostokątnym przekroju dla umożliwienia wizualizacji procesu spalania w kierunku prostopadłym do osi cylindra. Dla uniknięcia rysowania szkieł zamykających ściany cylindra zastosowano specjalne sprzęgło połączone z hamulcem, które umożliwia szybkie sprzęgnięcie koła zamachowego z mechanizmem korbowym, a następnie ich rozłączenie i zahamowanie wału korbowego. Cały cykl operacyjny maszyny zamyka się podczas dwóch obrotów wału. Przedstawiono szczegóły konstrukcyjne maszyny i charakterystykę przyspieszania tłoka, a także zaprezentowano przykład wizualizacji procesu spalania.