Optical study of the use of recirculated gases for adiabaticization of combustion process in the SIDI engine

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Abstract. Proper delivery of gaseous components of the charge into the combustion chamber enables controlling of combustion in the aspect of adiabaticization of the process. The adiabaticization obtained as result of surrounding of combustible mixture by recirculated exhaust gases should contribute to reducing formation of harmful components created during this process. The key issue here is the formation of radicals, which is not sufficiently recognized according fuels surrounded by non-combustible gases. The innovative nature of this work ensues from the experimental confirmation of so defined organizing of combustion process. Currently there are no tests concerning attempts of gas separation in the combustion chamber of engine with external source of ignition. Such separation would contribute to the increase of the adiabaticization process while at the same time the combustion rate increases and reduces the combustion duration. This paper presents the next stage of research, which were preceded by simulation and experimental investigations. In the article the results of the impact of the strategy of non-combustible gas injections on combustion ratios for cylinder head with a centrally positioned ignition point have been discussed. The analysis has been based on the photo material for the period from the start of ignition to full coverage of the cylinder by the flame. Authors performed a comparative analysis (against the recorded images) of the thermodynamic indexes of the combustion process obtained from the indicator traces.

1 Introduction

Internal combustion engines still play an important role as a power source for automobiles. Even though there has been a growing trend in the automobile industry to pursue development of hybrid electric vehicles (HEV) or plug-in hybrid electric vehicles (PHEV), innovation of internal combustion engines (ICE) is essential to maximize performance of these types of vehicle. In an era of stringent standards for fuel consumption and emissions of exhaust gases from vehicle drive systems [1, 2], one of the directions of development in the design of these systems is the use of alternative drive systems (hybrid, hydrogen drives) [3-5]. Traditional drive systems using spark-ignition combustion engines and compression-ignition engines are subject to modification [6-9], which can be summed up as actions involving downsizing, downspeaking, direct fuel injection, boosting and rightsizing [4, 10-12]. Possibilities presented by Isenstadt et al. [13] for reducing fuel consumption on the example of Skyactiv-G engine (Fig. 1) indicate the effectiveness of the application of the cooled exhaust gas recirculation system, particularly for medium engine loads.

One particular advantage of using exhaust gas recirculation systems is a relatively small increase in the cost of modifications. For this reason, virtually all modern engines are equipped with exhaust gas recirculation systems.

Fig. 1. Reduction in fuel consumption of Skyactiv-G 2.5T [13].

Some ideas of applying of flue gases for reduction in intensity of nitrogen oxides formation was formulated in early 80-th of XX c. However, the level of development of fuelling systems was not high enough for any spectacular progress at this time. Next ideas of this kind were proposed in 1993 by Heitland et al. [14]. Based on the patent application from early 1993 designed for two-stroke engines [15] they suggested to generate the region of air-fuel mixture in the central part of combustion chamber which should be surrounded by exhaust gases from previous cycle. For mixture formation the air-blast atomizer has been proposed, and tangential shaped

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exhaust channels for swirling of exhaust gases remaining around the mixture and isolating combustion process from cylinder walls.

Fig. 2. The conception of mixture-exhaust stratified charge combustion system for opened combustion chamber [15].

For practical realization of this system in open chamber the application of impinging jets has been suggested with electronically controlled fuel and air supplies, or – alternatively – an air assisted fuel injection – Fig. 3. Unfortunately, at that time the electronically driven injectors have not reached enough high level of development and the authors of this idea did not disposed the appropriate equipment for the experimental confirmation of its expected operation. With the present technical investigation possibilities, this task might be newly restarted.

Fig. 3. MESC-type engine with electronically controlled fuel supply and with pneumatic mixture injection [16].

In recent years as such it can be also considered the Turbulent Jet Ignition (TJI), which makes it possible to increase the thermal efficiency of the system up to about 45% [17, 18]. An actual research question should be the recognition of the impact of those prototype combustion systems, which can significantly reduce the emissions.

In order to meet the requirements of the above trends in development involving improving combustion efficiency, it is necessary to identify the essential processes taking place during combustion. One of the

methods of diagnostics of the fast-varying processes is the evaluation of the flame initiation and development. The authors of this article undertook the task of such assessment using the performed earlier simulation studies [19] concerning the control of the distribution of combustible and non-combustible gases in the cylinder chamber.

2 Motivation for undertaking the research issues

Earlier publications of the Authors concerning simulation [19] and experimental analysis with one modification of the cylinder head of the rapid compression machine (RCM) [20] have shown the benefits of the proposed solution to use non-combustible gases to control the process. The solution is associated with a reduction in the energy indexes of the process (caused by the reduction of the volume of the combustible mixture). However, the nature of combustion with its benefits in the form of reduced losses of heat exchange with the walls of the operating cylinder justify undertaking the subject. In order to increase the efficiency of the internal combustion engine, it is important to prepare properly the combustible charge in the chamber of the cylinder. The correct conditioning of the combustion process may allow the reduction of fuel consumption.

One way to meet the above demands is to use recirculated exhaust gases to introduce some volume of a non-combustible gas into the cylinder in a strictly defined way, involving the control of the space in which the combustion process will take place. According to the previously mentioned methods of gas distribution inside the cylinder [19, 20], it is possible to obtain several types of swirling: lateral, axial and radial. Radial stratification of the air and exhaust gases is the most suitable choice, from the point of view of the compression stroke, in terms of maintaining the stratification during piston movement. The interior region of the fuel-air mixture is encased in the exhaust gas region. Both of these regions are coaxial in the cylinder, and therefore the compression stroke should not disturb the load stratification (the separation of injected air and exhaust gas). In addition, if the angular momenta of the loads are kept during the compression stroke then a mass of air and exhaust gas swirling in the same direction will result in a much longer lasting stratification of the mixtures at the end of the compression stroke.

In contrast to the classic solutions supplying the recirculated exhaust gases into the cylinder chamber in combustion engines, the presented system involves supplying non-combustible gases in a strictly defined manner. Presented in the paper [21], as well as in [14-16], possibilities of stratification of a charge with non-combustible gases (separation of air and exhaust gases) allowed the Authors to choose the concept of a combustion system from among several earlier proposals.

Charge stratification can be divided into lateral (starting from the left), axial and radial [21]. Radial

stratification of the discussed gases (air and exhaust gases) from the point of view of the compression stroke is the most suitable choice in terms of preserving stratification during the movement of the piston. An outer layer of the exhaust gases is surrounding the internal area of the air-fuel mixture. Both layers are coaxial in the cylinder of the engine; therefore the compression stroke should not interfere with the separation of the charges of combustible and non-combustible gases. In addition, if during the compression the air momentum and exhaust gas momentum are preserved, then the air and gases swirling in the same direction will result in much longer retention of the mixtures stratification at the end of the compression stroke. Figure 4 shows the implementation of the assumptions using RCM.

Fig. 4. The implementation scheme of the provide gases to the RCM.

Presented in publication [20] analysis of possibilities of obtaining the combustion process adiabaticization in the designed system of lateral excitation of the ignition, indicated obtaining radial stratification, which made it possible to separate air from the exhaust gases in the area of the combustion chamber (in the SIDI engine). Test results indicated restriction in the access of the flames to the cylinder walls. The obtained reduction in the surface area of the flame amounted from 13% to 50% (for three repetitions of the combustion process) compared to combustion of fuel only with the participation of air.

3 Research object

For the tests was used the Rapid Compression Machine (RCM) with the parameters shown in Table 1. Upgrades in relation to the previously presented designs of the combustion chamber [20] involved different location of the spark plug in the cylinder head. In the presented tests the spark plug is placed in the centre of the chamber (Fig. 5) (11). The injector (10) and the inlet valve of air (12) and non-combustible gases (13) are positioned as shown in Fig. 5.

Table 1. Characteristic of RCM.

Quantity	Value
Stroke	89 mm
Bore	80 mm
Volume of combustion chamber	55 cm ³
Method of delivery non-combustible gases	solenoid valves
Compression ratio	11
Type of combustion chamber	hemispherical chamber in the head + chamber in the piston
Optical access	from the bottom of the combustion chamber, quartz glass $\phi 50$ mm arranged in the piston

Previous studies of the Authors [20] proved the thesis that it was possible to conduct combustion in the presence of recirculated exhaust gases. However, due to positioning of the spark plug in the lateral part of the head, the Authors decided to modify the system, so that now it is in the central part of it. The aim was to increase the concentration of combustible charge in the centre of the combustion chamber, allowing for greater concentration of the flame in the combustion chamber with limited access to the cylinder walls.

4 Research methodology

The tests on combustion process were conducted with the use of two main measurement systems (Fig. 5):

- the system for acquisition of measurements of fast-varying signals (3),
- the system for acquisition high-speed imaging of combustion process (5, 6).

Fig. 5. A 3D design of the test bench (explanations in text).

The other elements necessary to conduct the presented tests were a triggering system – a sequencer (1, 2), a valve control (4), a compressor (7), RCM (8), and a non-combustible gas bottle (9).

The tests were conducted for 3 different sequences of the inlet of non-combustible and combustible gases into the combustion chamber, and for various values of non-combustible gas injection pressure. Gas inlet sequences were as follows:

- Initial air injection into the chamber through the valve (12), then injection of CO₂ through the valve (13),

- II. Initial injection of CO₂ into the chamber through the valve (13), then injection of air through the valve (12),
- III. Simultaneous injection of both gases.

The tests results were compared to the reference measurements, where the injection of CO₂ was not used.

5 Thermodynamic indexes of combustion process

Comparison of the characteristics of indicated pressure in the combustion chamber is shown in Fig.6. The characteristics of three sequences of non-combustible gas injection into the combustion chamber were compared to the reference characteristics. For each case three measurement points corresponding to the pressures of CO₂ injection 5, 7, 10 bars are presented. Based on the increase of pressure in the combustion chamber prior to the movement of the piston, the portions of the non-

combustible gases in relation to combustible mixtures were determined during the tests, and they amounted to respectively 20 and 32% of the charge volume. These values are variable within a range of $\pm 5\%$ depending on the sequence of the injection of gas into the chamber.

The areas of maximum delay for $P_{\max}$ values in relation to the reference point are shown on the diagrams. The biggest delay in occurrence of maximum value of this parameter is observed for the characteristics of sequence II, where for the injection pressure of CO₂ of 10 bars was observed over 25 ms delay in the occurrence of the $P_{\max}$ value in comparison to the reference point. Sequence III – simultaneous injection of combustion air and CO₂ – was registered with the maximum delay $P_{\max}$ lower by 20% from sequence II. The slightest delay in occurrence of $P_{\max}$ value at the CO₂ injection pressure of 10 bars was registered for sequence I (it amounted to 8 ms) which represents 60% of delay compared to sequence II.

Fig. 6. Indicated pressure characteristics at different sequences of injection of air and non-combustible gases.

Fig. 7. Characteristics of heat release rate for the analysed sequences of CO₂ injection.

The maximum reported values of the combustion pressure in the RCM chamber were less than for the reference point. The smallest decrease in of $P_{\max}$ when compared to the reference point was recorded at the injection pressures of CO_2 of 5 to 10 bars for sequence III. Possible causes of only a several-percent decrease in the value of the $P_{\max}$ were an early creation of swirling and combustible areas around the centre of the cylinder. This has allowed achieving combustion without significant deterioration of operating parameters. In the sequences I and II, in which gases are supplied at intervals, charge distribution is differentiated, which affects the process of combustion. For these sequences were recorded decreases in $P_{\max}$ pressure by 19% for sequence I and 36% for sequence II, at non-combustible gas injection pressure amounting to 10 bars in relation to the reference characteristics.

An increase in the share of non-combustible gases in the combustion chamber by increasing the injection pressure of CO_2 deteriorates the combustion process in terms of the value of heat release rate (dQ), which is shown in Fig. 7.

Comparing to the reference characteristics (100%) it was observed that the heat release rate was reduced for sequence I from 51 to 85%, for sequence II from 78 to 95% and for sequence of III from 33 to 81%. Conditions of changes in heat release rate indicate suppression of the combustion process by addition of non-combustible gases. This process is inevitable in the assumed prototype system of combustion control. It is important, however to recognize the possibility to control the combustion process, depending on the selected sequence of injection of CO_2 .

The next stage of the research could therefore be analysed taking into account the change in dose of the injected fuel. Such parameters may allow to obtain the value of the combustion process at the level of the reference characteristics. Comprehensive coverage of more variable parameters, however, affects the size of

the measurement matrix extending the time of tests and increasing the range of research material.

6 Optical analysis of the combustion process

Along with recording of the indicated pressure, also the optical recording of the combustion process took place, utilizing for this purpose the optical access in RCM from the bottom of the piston through quartz glass mounted in the piston crown. The frequency of recording was chosen for 5 kHz allowing registration of images with a resolution of 624×1024 pixels.

In order to specify the area the flame takes up during combustion in a given system, the recorded data was the subject of digital processing consisting of (show in Fig. 8): (1) defining the viewing window area mask, then (2) choice of analysis area and (3) counting the pixels whose radiation intensity was higher than the background noise. Then, by registering the triggered discharge on the spark plug, it was possible to determine a common time baseline for the indicator and optical research results (synchronization).

Fig. 8. The course of processing the optical test results.

Fig. 9. Analysis of the flame area history in the combustion chamber.

Optical registration of two-dimensional (planar) flame exposure has allowed the determination of the area occupied by the flame in the chamber. For this purpose, a macro of DaVis software was used. Figure 9 shows the results of the calculations of the area of the flame. In consequence (in relation to Fig. 4) the colours and markings used show in succession the areas of reference flame for sequence I, II and III. For the reference measurements, a sharp increase of the flame in the chamber was recorded, on average involving over 80% of the optical window in the piston. The flame in this configuration is maintained for a longer period of time in the optical window, which point to a long combustion process.

The use of non-combustible gas injection into the chamber resulted in significant differences in the recorded image of the combustion process. The presented selected results of tests at 3 different injection pressures of CO₂ show direct influence of the increase of the non-combustible gases dose of on the area occupied by the flame. Combustion at the injection pressure of CO₂ equal to 5 bars results in a slight decrease to the level of 75% of the covered exposure by the flame, the elongation of the combustion process and the lack of previously observed after-burning phase (for sequences I and III).

With increasing pressure of CO₂ injection, the area of the flame decreases to a value of about 50% for a sequences I and III, and to 15% for the sequence II. A decrease of the flame area by 80% (sequence II, $P_{CO_2} = 10$ bar) indicates high by volume concentration of the process of combustion by non-combustible gases. The frame-by-frame analysis indicates the limitation of this process, which is concentration of the flame in the middle of the cylinder. Reduction of the light intensity (luminance), also indicates a reduction in flame intensity.

For the sequences I and II was reported elongation of the combustion process from 50 to 300% relative to the reference point, without taking into account the afterburning phase (flame area below 5% in Fig. 7). In the reference combustion process, however, there was reported reference long-lasting process of afterburning of the flame in the vicinity of the cylinder wall. Such burning is very unfavourable due to the likely formation of soot particles. Non-flammable gas injection tangential to the axis of the cylinder allowed for the introduction of the assumed gas swirling in the chamber in such a way that they surround the resulting flame. Such a way of supplying gases allowed to restrict the spread of flame in the cylinder in a controlled manner, limiting its spread from the centre of the combustion chamber. Analysis of flame areas provided in Fig. 10 shows selected illustrations of flame with interval of 1 ms. In the reference characteristics can be observed persistence of the flame within the cylinder walls. Sequence II is characterized by the greatest suppression of the combustion process and its concentration in the centre of the cylinder. In contrast, sequences I and III are characterised by longer time of spreading of the flame.

Fig. 10. Comparing the flame area for the presented sequences ($P_{CO_2} = 10$ bar).

The highest flame intensity (for a reference sequence occurring after 6.4 ms) appears in sequence I – after 12.8 ms, in sequence II – after 15.6 ms, and in the third sequence – after 7.4 ms. This means that the maximum flame area instance delay is, respectively, 100, 140 and 15% for non-combustible gases and injection pressure of

10 bars. The diversity of these times results from different supply of the non-combustible gases and different organisation of the combustion process.

Based on the results of experimental studies a conclusion can be presented concerning the benefits of different ways of supplying combustible and non-combustible gases:

- sequence III (that is, the simultaneous supply of gases into the chamber) intensifies the combustion process in the centre of the chamber and at the same time allows its quick conclusion,
- sequence II delivering first non-combustible gases and later air, makes it possible to concentrate combustion in the centre of the combustion chamber, increasing the adiabaticization of the process.

It seems that the sequence II is more desired because of the organisation of the combustion process (high concentration of flame around the centre of the combustion chamber), adiabaticization of the process (limited heat exchange) and the creation of harmful components (combustion showing characteristics of the low temperature combustion with limited potential for creation of nitrogen oxides).

7 Summary

Thermodynamic analysis of the combustion process of different variants of delivering air and non-combustible gases into the combustion chamber indicates that the smallest deterioration of performance of RCM is observed for sequence III. Also the optical analysis of the combustion process indicates the smallest its elongation of the above-mentioned sequence.

The proposed system makes it possible to introduce for controlling the additional system variables such as: changing the portion of non-combustible gases by extending injection time, advancing of flue-gas injection or division of the injected portions of these gases, and simultaneous control of the process relating to fuel dose quantity and time of injection. The variation of these variables enables in big extent the optimization of the combustion course, especially for sequences I and II (see chapter 4). The above conclusions are justified by the highest concentration of the flame in the centre of the cylinder observed for sequence II.

The presented tests are basic research, showing the validity of thesis that the combustion process can be controlled using non-combustible gases in such a way as to limit the exchange of heat (during combustion) with the cylinder walls. Further analysis of the combustion process will apply to local flame temperature analysis using the two-colour method of optical research. This will make it possible to associate the global indicators of the process with local temperature values in the combustion chamber.

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