Evaluation of the combustion process in a spark-ignition engine based on the unrepeatability of the maximum pressure

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Abstract. The article presents the results of an empirical study of unrepeatability of the spark-ignition engine BMW N43 B20 AY, which uses a spray-guided gasoline direct injection system to create the fuel mixture. The values of the so-called unrepeatability index of maximum indicated pressure were analysed for two different engine operating conditions: under maximum load (absolute throttle at 91%) and under partial load (absolute throttle at 33%). The values of the index were calculated on the basis of values of indicated pressure recorded over 100-cycles at five predefined rotational speeds of the engine crankshaft. It was found that the unrepeatability of maximum indicated pressure during operation of the test engine was lower under partial load than under maximum load.

1. Introduction

The examination tests of internal combustion engines give the opportunity to determine the impact of design and operation factors on the combustion process. It is also possible to change the parameters of the engine control. The previous scientific and research work of the authors of the article included tests of diesel engines aimed at determining the impact effect of some properties of hydrocarbon fuels on self-ignition delay [1-3]. In the case of spark-ignition engines, analyses of structural changes to exploitation characteristics were carried out [4,5].

The essential operational processes occurring in combustion engines are periodically variable over time. They are accompanied by stochastic fluctuations. Random changes in the combustion process in the successive circulations and individual engine cylinders are caused mainly by uneven air supply to the cylinder and unrepeatable removal of exhaust gas into the exhaust system, the occurrence of wave phenomena and turbulence in gas media, variability in the degree of turbulence of gas in the cylinder affecting the combustion process (the movement of flame front and heat exchange), lack of ignition of the combustible mixture in the cylinder (misfiring), the unrepeatability of spatial distribution of load in the combustion chamber, wave phenomena in the injection system which cause variable load composition in the cylinder, rotational speed fluctuations due to stochastic variation of the force of friction (lubricating film thickness) between the piston and the cylinder and fluctuations of torque loading the crankshaft. These fluctuations cause the so-called unrepeatability of combustion engine operation. Incomplete repeatability of successive engine cycles is a constant phenomenon, even at high stabilization of load parameters.

Parameters related to pressure in the cylinder are also often used for diagnostic purposes. They signal, among others, the misfire phenomenon, which causes unrepeatability of engine operation. The value of maximum cylinder pressure in successive work cycles, which is recorded in indicating studies, is usually

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adopted as a representative value for analysing the unrepeatability of engine operation. The values of maximum pressure in successive indicator diagrams should be treated as random variables. An analysis of the unrepeatability of maximum indicated pressure requires the application of statistical methods. The empirical coefficient of variation is a recognized index of unrepeatability of maximum indicated pressure [6].

Combustion systems in spark-ignition engines which use a spray-guided gasoline direct injection system to create the fuel mixture in the cylinder are capable of running on very lean mixtures. Compared to engines running on homogeneous mixtures, engines with spray-guided systems have lower fuel consumption and lower emissions of toxic components of exhaust fumes. Therefore, the analysis of the unrepeatability of operation of this type of engines is an interesting research topic [7-10].

2. Description of the test station

The object of the study was a naturally aspirated four-cylinder spark-ignition engine BMW N43 B20 AY with a displacement of 1995 cm3, maximum power of 105 kW (143 hp) at crankshaft rotational speed of 6200 rpm and maximum torque of 190 Nm at crankshaft rotational speed of 4250 rpm The test engine was equipped with the variable valve timing system, Vanos – a spray-guided combustion system for the preparation of mixture in the cylinder. Control of variable valve timing is dependent on engine load and speed. At medium rotational speeds, a controller rotates the camshaft so the valves are opened earlier, thus increasing the valve overlap angle. At engine speeds exceeding 4500 rpm, the controller decreases the valve overlap angle.

The test bench was equipped with a ZOLLNER-KIEL AVL Alpha 240 eddy current brake with a power rating of 240 kW, a maximum speed of 10,000 rev/min, and a maximum torque of 600 Nm. A schematic diagram of the test bench is shown in Figure 1

The measuring chain for the measurement of pressure in the combustion chamber consisted of the following elements: a Type 3057-V01 load amplifier, a GH12D piezoelectric pressure sensor, a crankshaft position sensor, a DAQPad-6070 measuring card, and an OBD II diagnostic interface (S-TECH, ST-OBD). During the tests, changes in indicated pressure in the cylinder as a function of crank angle over 100 consecutive combustion cycles were recorder. Also recorded were the operating parameters of the engine supply system: calculated engine load, throttle opening angle, air flow, rotational speed of the crankshaft, ignition advance angle, coolant temperature, composition of the fuel-air mixture (as indicated by lambda air-fuel ratio sensors), fuel pressure, and intake air temperature,

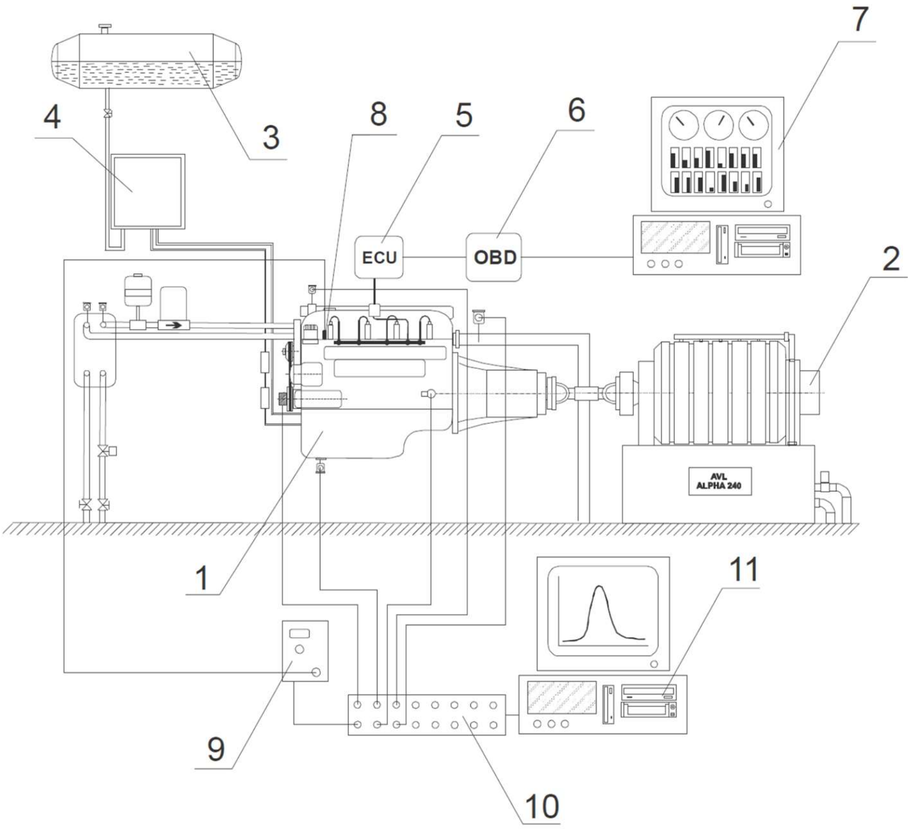

Figure 1. A schematic diagram of a measurement chain for testing indicated pressure 1 – engine, 2 – eddy current brake, 3 – fuel tank, 4 – fuel consumption gauge, 5 – engine controller, 6 – OBD II diagnostic interface, 7 – computer for recording the operating parameters of the engine, 8 – indicated pressure sensor, 9 – load amplifier, 10 – measurement card 11 – measuring computer for recording indicated pressure.

3. Evaluation of unrepeatability of combustion under fixed operating conditions

To assess the degree of unrepeatability of combustion under fixed conditions, was used maximum indicated pressure [6]. The unrepeatability of engine operating parameters was analysed within a given sample at speeds of 1500, 2000, 2500, 3000, 3500 rpm under engine operating conditions corresponding to maximum load (external characteristic – absolute throttle 91%) and partial load (external characteristic of partial power – absolute throttle 33%). For each engine cycle, the maximum indicated pressure was determined.

Figures 2 and 3 give examples of open indicator diagrams illustrating mean indicated pressures of the test engine at loads of 33% and 91% and rotational speeds of the crankshaft of 1500 and 2500 rpm, respectively. When the engine operated under medium and maximum loads at a rotational speed of 1500 rpm, there was a significant increase in maximum indicated pressure at the load of 33% in comparison to the 91% load. The difference in pressure was 0.76 MPa. Additionally, the angle of maximum pressure was shifted by 24 °CA (Figure 2).

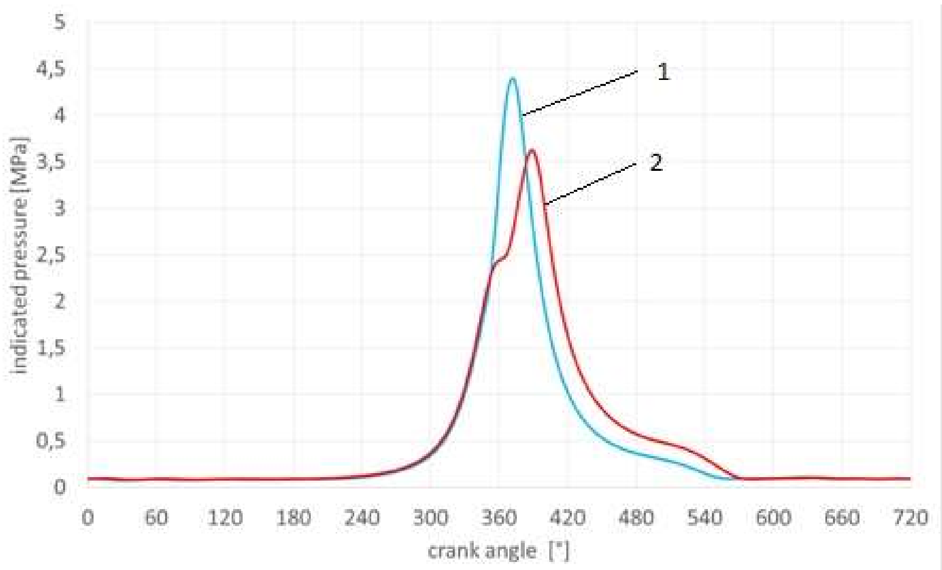

Figure 2. A comparison of open indicator diagrams obtained under the conditions of the external characteristic (91%)- curve 2 and partial load (33%) – curve 1 at a rotational speed of the engine crankshaft of 1500 rpm.

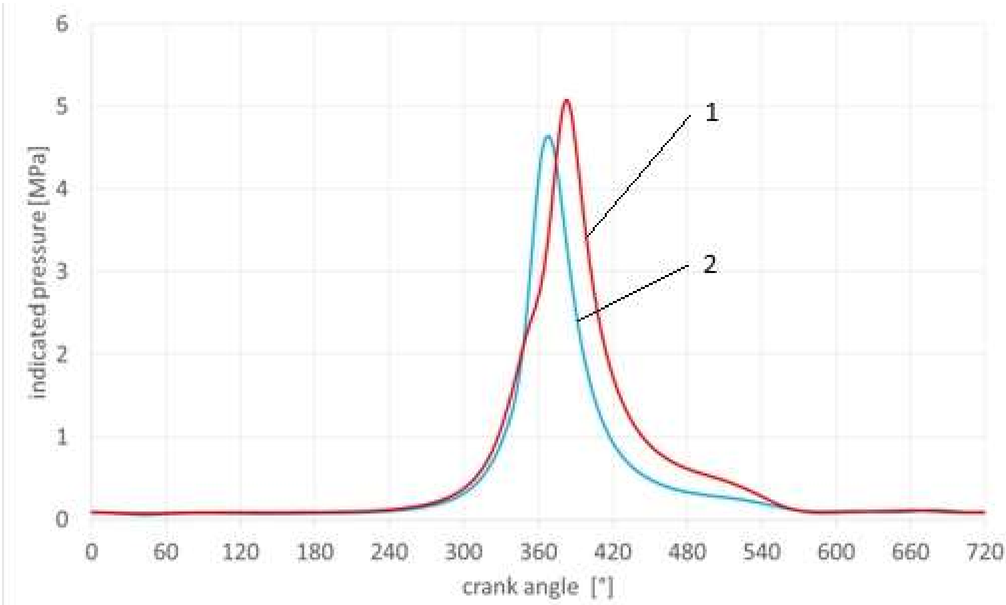

Figure 3. A comparison of open indicator diagrams obtained under the conditions of the external characteristic (91%) – curve 1 and partial load (33%) – curve 2 at a rotational speed of the engine crankshaft of 2500 rpm.

Figure 3 shows mean indicated pressures of the engine operating at medium and maximum loads at the speed of 2500 rpm. At 91% load, the maximum indicated pressure recorded was 5.1 MPa at a CA of 384°. At 33% load, the maximum indicated pressure recorded was 4.60 MPa at a CA of 364 °. The shift in maximum pressure was 20 °CA.

Compiled of open indicator diagrams for the engine operating at medium and maximum loads over the range of speeds tested (1500, 2000, 2500, 3000, 3500 rpm). Within this speed range, maximum indicator speeds were in the range of 4.46 to 5.39 MPa at the load of 33%, and 3.96 to 5.05 MPa at the load of 91%.

During the analysis of changes in the indexes of unrepeatability of maximum pressure as a function of the rotational speed of the engine crankshaft (Fig. 4), it was noted that the distribution of points at the medium load (33%) was more uniform (values in the range of 0.04 to 0.07) than at the maximum load (91%), for which the distribution values were in the range of 0.08 to 0.11, and oscillated around a mean of 0.09. This shows that at the higher engine load the unrepeatability of the maximum pressure was greater than at the partial load. At the partial load (31%), engine operation was practically stable

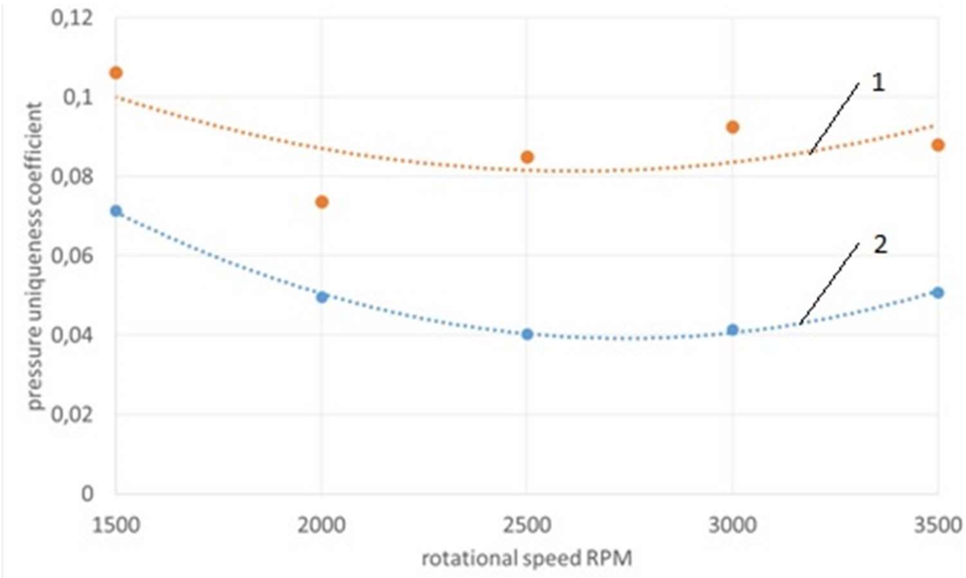

Figure 4. The unrepeatability of the successive operation cycles at different rotational speeds of the engine crankshaft for the medium load (31%) – curve 2 and for the maximum load (91%) – curve 1.

The unrepeatability of the maximum combustion pressure in 100 successive engine operation cycles at different rotational speeds and loads is shown in Figures 5 - 8. In the graphs showing indicator pressure at the maximum engine load, one can note that in some cycles maximum pressure had values which were considerably higher than others. This was probably due to abnormal combustion in the previous cycle, in which the value of maximum pressure was below the mean. These differences may be a consequence of the unrepeatability of cylinder filling with fresh charge as well as the variability of fuel dose, the occurrence of wave phenomena in the intake and exhaust manifolds, the variability of the ignition advance angle, and the occurrence of multiple spark discharge during one combustion cycle.

When the engine was running at the medium load, the maximum values of indicated pressure in the individual cycles were characterized by smaller scatter. At the same time, there was an increase in maximum pressure values with an increase in the rotational speed of the engine crankshaft.

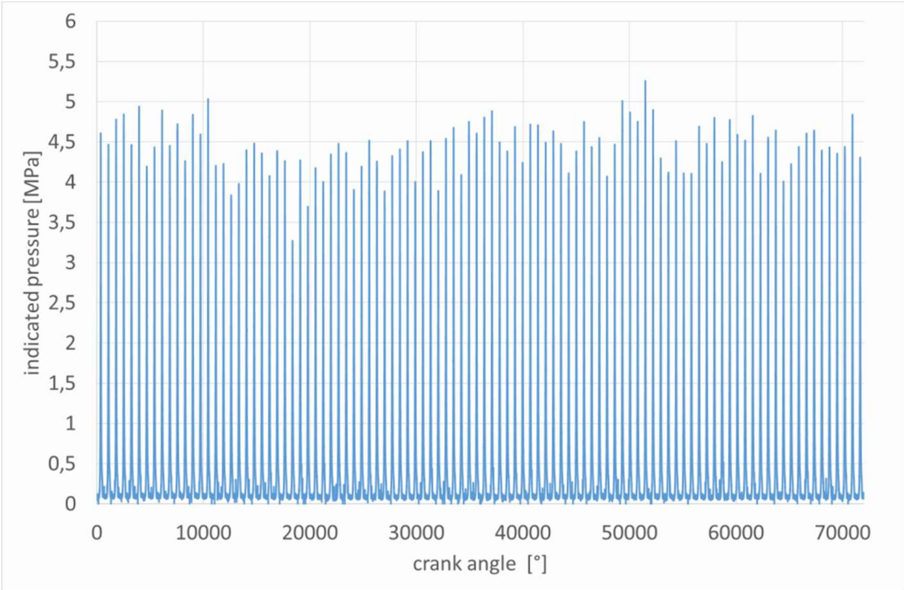

Figure 5. An indicator diagram of 100 engine operation cycles at 33% load and the engine rotational speed 1500 rpm.

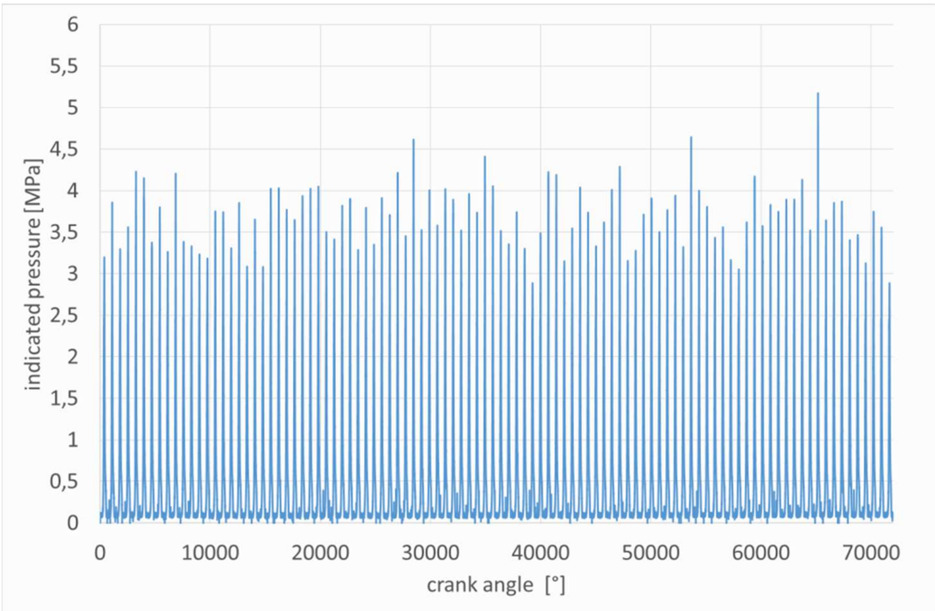

Figure 6. An indicator diagram of 100 engine operation cycles at 91 % load and the engine rotational speed 1500 rpm.

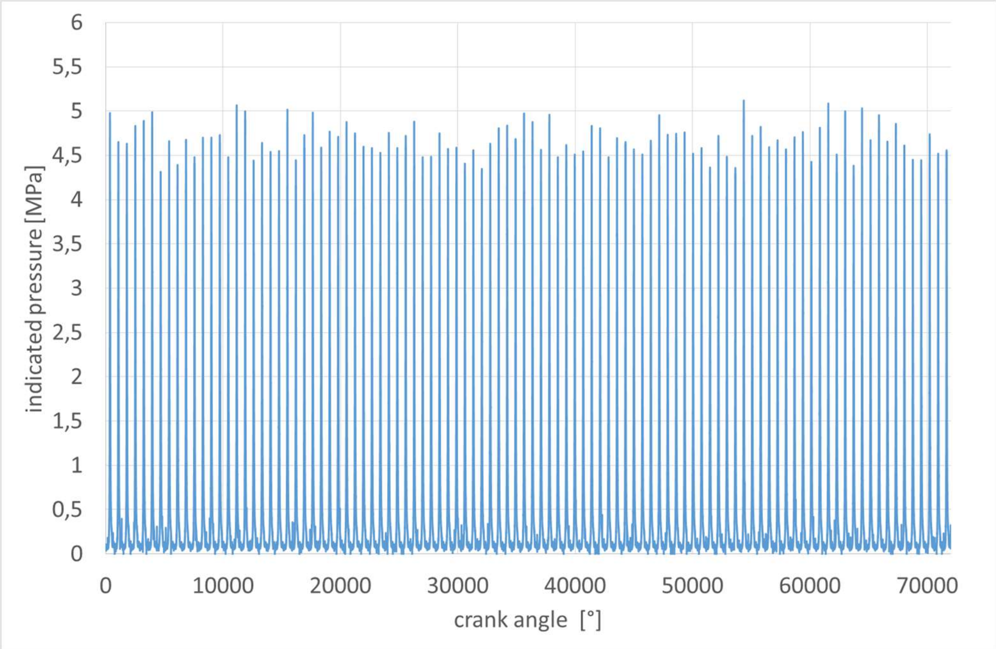

Figure 7. An indicator diagram of 100 engine operation cycles at 33% load and the engine rotational speed 2500 rpm.

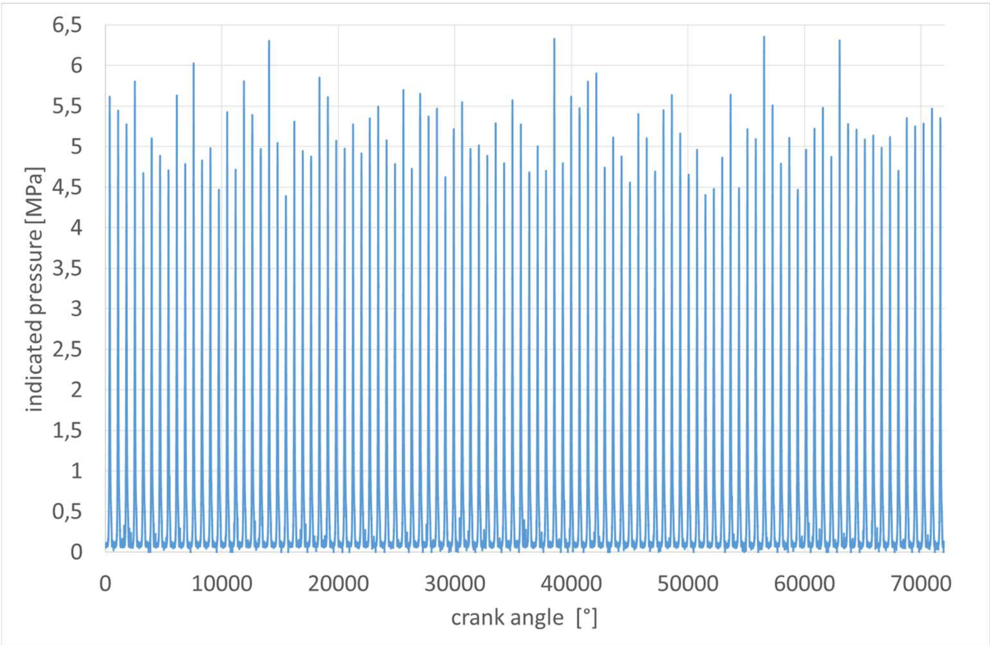

Figure 8. An indicator diagram of 100 engine operation at 91 % load and the engine rotational speed 2500 rpm.

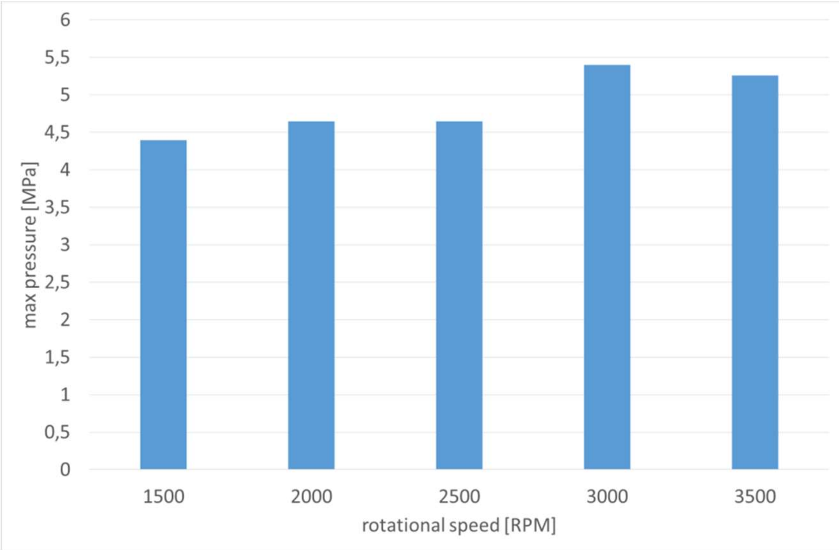

Figure 9. Mean values of maximum indicated pressure calculated for 100 cycles at the load of 33%, as a function of engine rotational speed.

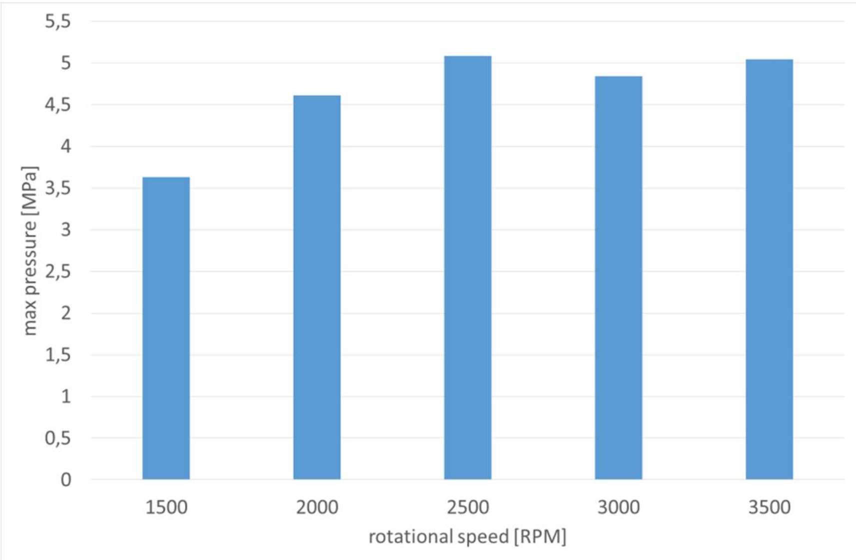

Figure 10. Mean values of maximum indicated pressure calculated for 100 cycles at the load of 91%, as a function of engine rotational speed.

Figures 9–10 show a comparison of the mean values of maximum indicator pressure calculated for 100 operation cycles at the loads of 33% and 91%, respectively, at the tested rotational speeds of the engine crankshaft. Under the medium load, the highest mean value of maximum indicator pressure was 5.39 MPa, which corresponded to the crankshaft rotational speed of 3000 rpm, and at the maximum load, this value was 5.09 MPa and corresponded to the crankshaft speed of 2500 rpm. The reason for this phenomenon was that the organization of the combustion process changed with the change in load. There was a transition in engine operation from the combustion of stratified lean mixture through combustion of stoichiometric homogeneous mixture to rich homogeneous mixtures.

4. Summary

The analysis of the results of the tests leads to the following conclusions:

1. The values of indicated pressure obtained during the bench tests should be considered reliable because the maximum parameters of engine performance recorded during those tests were consistent with the data provided by the manufacturer. Maximum pressure varied in the range of 0.22 to 0.58 MPa at the medium engine load, and from 0.09 to 1.01 MPa at the maximum load and rotational crankshaft speeds in the range of 1500–3500 rpm.
2. The values of the index of unrepeatability of maximum pressure at maximum load and rotational speeds of the engine crankshaft of 1500, 2000, 2500, 3000 and 3500 rpm tend to stabilize around the value of 0.09, which leads to the conclusion that, at the maximum load, engine work is characterized by notable unrepeatability. The values of the index of unrepeatability of maximum pressure under partial load tend to stabilize at the level of 0.05 at rotational speeds of 1500, 2000, 2500, 3000 and 3500 rpm. Such a low value of the index shows that engine operation in this range of speeds is stable. This observation stands in contrast to other reports on the unrepeatability index found in the literature of the subject. This fact can probably be explained in terms of the impact of the control system of the BMW N43 B20 AY engine, which implements different combustion strategies depending on engine operating parameters (rotational speed, load). Further research is needed to confirm this hypothesis.
3. The analysis of scatter of the values of maximum pressure shows that at the rotational speed of the engine of 3000 rpm, the scatter of values is in the range of 4.46 to 5.39 MPa at the load of 33%, and 3.96 to 5.05 MPa at the load of 91%. This confirms the conclusion formulated earlier.
4. A comparison of mean values of maximum indicated pressure at engine loads of 33% and 91%, and rotational speeds of 1500, 2000, 2500, 3000 and 3500 rpm, showed that maximum pressure values correlate with the time course of torque development at the investigated loads.

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