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Stationary installation for studying the combustion process of methane fuel in an engine

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Abstract. The study of combustion processes in the KAMAZ engine of the 820.60 series, running on compressed natural gas with forced ignition, is proposed to be carried out using the indexing method on a stationary laboratory installation. The composition of the equipment necessary for recording the combustion process and subsequent analysis has been determined. The criteria for the parameters of the pressure sensor, the characteristics of the analog-to-digital converter, the characteristics of detonation sensors and gas-air mixture composition sensors were taken into account. The installation locations of the sensors and the schemes for their coordination with the data acquisition system and the software functions for recording and processing signals have been determined.

1 Introduction

Compressed natural gas today is the main alternative to liquid hydrocarbon fuels traditionally used in internal combustion engines [1-3]. One of the methods for improving the power and economic characteristics of spark-ignition engines running on gas engine fuel is to increase the compression ratio. However, the limiting factor is the occurrence of detonation when a certain threshold value of the compression ratio is reached [4-5].

The parts of the engine that are susceptible to breakdown due to improper combustion of the fuel-air mixture in the combustion chamber are the cylinder heads and the cylinder-piston group. During the detonation process, temperature and pressure increase in a short period of time [6-10], causing a critical, destructive effect on the parts of the internal combustion engine (ICE) [11], which significantly affects the performance, service life and reliability of the power plant.

The purpose of this study is to register possible detonation and determine the criteria for its occurrence during the combustion of compressed natural gas in the KAMAZ engine of the 820.60 series in combination with the serial electronic control unit ABIT M20.21.

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2 Materials and methods

It is known that detonation can cause the following phenomena: scuffing of the piston and cylinder surface due to the choice of clearance due to overheating; in unfavorable conditions, the piston may become jammed, causing the connecting rod to be torn off and the crankcase or cylinder head to be perforated; burning or even burnout of pistons, cylinder heads and valves, destruction of spark plugs due to burning and melting of electrodes and cracking of insulators with subsequent chipping.

Figure 1 shows a piston that has failed, presumably due to detonation of the gas-air mixture in the combustion chamber of the KAMAZ 820.60 internal combustion engine.

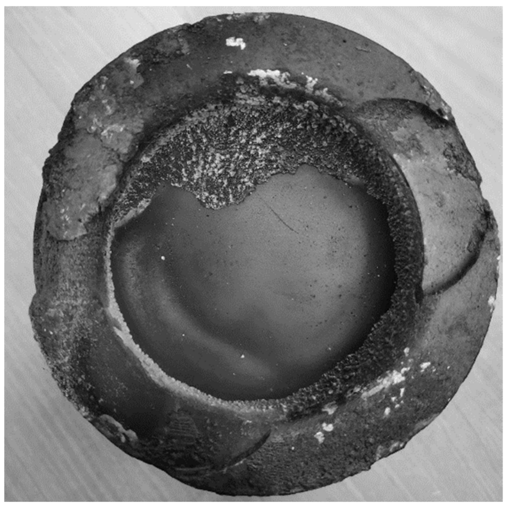

Fig. 1. Piston failed due to detonation.

Figure 2 shows typical damage resulting from normal detonation and superdetonation [12].

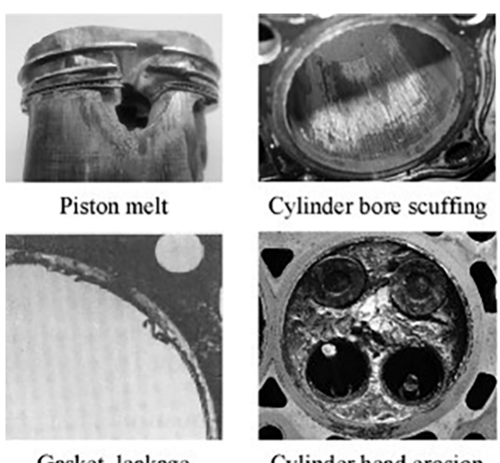

Fig. 2. Types of damage resulting from detonation combustion.

Figure 3 shows damage caused by high pressure and high temperature due to detonation combustion [13].

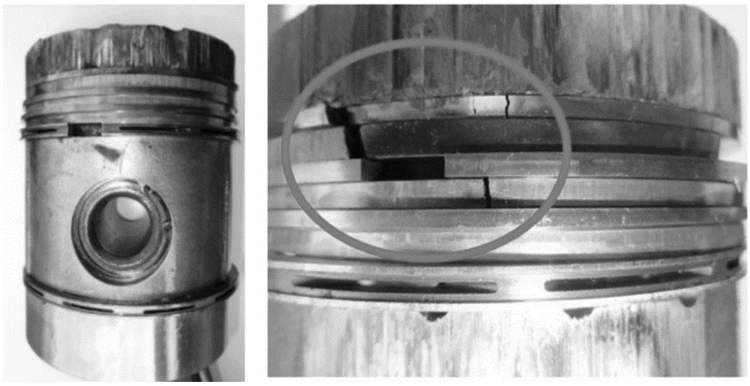

Fig. 3. Damage to the piston and rings.

The consequences of detonation combustion listed above allow one to note that detonation significantly affects the reliability parameters of units. The search for means to combat detonation is a subject of research aimed at increasing the efficiency and reliability of internal combustion engines [11, 14-15].

One of the factors influencing detonation combustion in the KAMAZ 820.60 internal combustion engine is the lack of means for controlling detonation combustion in serial versions and, therefore, imperfect algorithms for preventing detonation [16]. This can be especially obvious when engine parts wear out, which still allows us to talk about a serviceable unit, but already affects the combustion processes. The work [17] presents the load characteristics of the engine model 8212.10-112 with a compression ratio of 11.5 and a turbocharger, similar in characteristics to the engine under study. At intake air temperatures not exceeding 25°C, the possibility of detonation is shown even at this intake air temperature. It can be assumed that when detonation combustion is detected on the engine under study already at partial load modes, at maximum loads of a vehicle tested during industrial operation, a more pronounced effect of detonation combustion on the appearance of the "leaky cylinder head" defect will be observed.

Based on the above, the study of the causes and registration of possible detonation during the combustion of compressed natural gas in the KAMAZ 820.60 internal combustion engine using the serial electronic control unit ABIT M20.21 on a laboratory installation of the KAMAZ 820.60 engine is of great interest.

2.1 Descriptions of installation of the KAMAZ 820.60 engine stand

The experiments will be carried out on an eight-cylinder KAMAZ 820.60 engine with variable parameters (Figure 4). The design of the stationary stand makes it possible to accurately control and change the operating parameters of a spark-ignition piston engine, such as crankshaft speed, coolant temperature, and ignition timing. The design features of the stand provide analysis of the influence of a specific factor on the combustion process. Thus, this stand makes it possible to repeat test modes, which is necessary to study the combustion process. Compressed natural gas - methane is used as fuel during testing at the stand.

Fig. 4. KAMAZ 820.60 stationary engine stand.

2.2 Description of the mobile complex for registration and processing of internal combustion engine parameters

Piezoelectric sensors can be used as primary transducers to study pressure in the combustion chamber [18]. This method is used to measure pressure in gases; it has high sensitivity and accuracy in measuring pressure and allows one to obtain fairly accurate data; it is well suited for indicating internal combustion engines [19-23]. The measured data will be the basis for the analysis of detonation in internal combustion engines [24-25]. From the analysis of publications [26-35], it follows that the pressure sensor PDD-200-M14-19 with a measurement limit of 200 bar and overall dimensions: thread M14x1.25, length of the threaded part 19 mm, which does not require cooling, is well suited for indicating the engine under study.

The characteristics of the SDD-200-M14-19 sensor are shown in Table 1.

Table 1. Characteristics of SDD-200-M14-19 sensor.

Names	Characteristic
Sensitivity, pC/bar (determined by the manufacturer individually for each sensor during calibration)	2.01
Measurement limit, bar	200
Error, %	3
Temperature limit, °C (temperature of the cylinder head in the vicinity of the spark plug)	300
Natural frequency of mechanical vibrations, kHz	> 50
Wire length, m	1.5

The cylinder pressure recording circuit should consist of a piezoelectric pressure sensor, a charge amplifier, a data acquisition system, and software [36]. The pressure sensor generates a charge under mechanical stress (strain) that is proportional to the applied pressure [24]. The signal amplifier converts the charge level generated by the sensor into a voltage signal. Coordination of work should be carried out by specialized software that allows you to parameterize the measuring system and the measurement process itself, calculate the characteristics of the internal combustion engine operating process and display the measured and calculated values. The software must be able to export measured and calculated data for subsequent processing using more sophisticated methods.

Information about the pressure in the cylinder is recorded together with information about the position of the angle of the crank mechanism using a crankshaft angle sensor relative to top dead center.

To comprehensively consider the factors influencing the occurrence of detonation combustion in the engine under study, it is necessary to record the actual composition of the fuel-air mixture. It was noted in [37] that impurities can significantly affect the methane number of gas engine fuel, that is, increase the tendency to detonation. When the methane number decreases by 5 units, the internal combustion engine may reach the detonation limit, and in this case, to eliminate detonation in engines with an electronic control system, two methods are usually used - reducing the ignition timing and the process of changing the mixture composition by adjusting the throttle valve. In [38-39] it is shown that engines equipped with control systems with feedback on the composition of the fuel-air mixture can operate with a wide range of gas compositions, maintaining a mixture composition that allows it to avoid detonation combustion. To record the excess air coefficient, a broadband LSU 4.9 sensor [40] is used, the parameters of which are given in Table 2.

Table 2. LSU 4.9 mixture sensor parameters.

Parameter name	Parameter value
Excess air ratio measurement	From 0.65
Exhaust gas pressure, bar	Not more than 2.5
Maximum exhaust gas temperature (long-term operation mode), ºC	930

Figure 5 shows the location of the excess air ratio sensor.

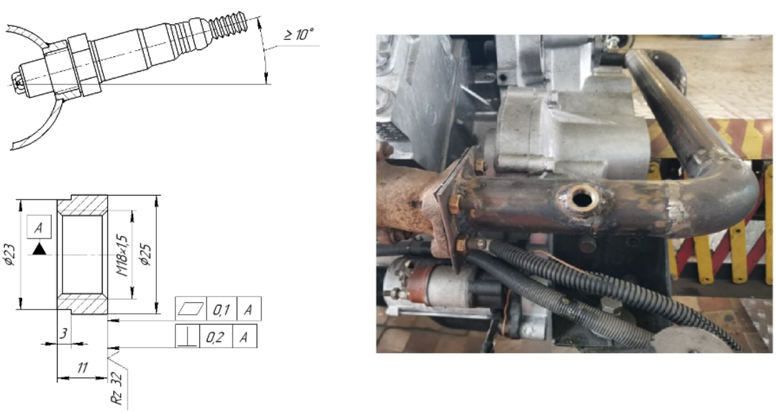

Fig. 5. Diagram and photo of the location of the sensor for measuring the composition of the gas mixture.

The criteria described in [41-42] suggest that the KS4-P sensor, the main characteristics of which are given in Table 3, is well suited as a detonation detection sensor.

Table 3. Characteristics of KS4-P knock sensor.

Parameter name	Parameter value
Sensor type	Piezoelectric
Sensitivity (at 5 kHz), mV/g	26 ± 8
Electrical capacity, pF (no more)	1150 ± 200
Output resistance, Mohm	>1
Linearity 5 to 15 kHz (from 5 kHz value)	From -10% to +10%
Weight, kg	0.048
Frequency range, kHz	3-25

Figure 6 shows the location of the knock sensor.

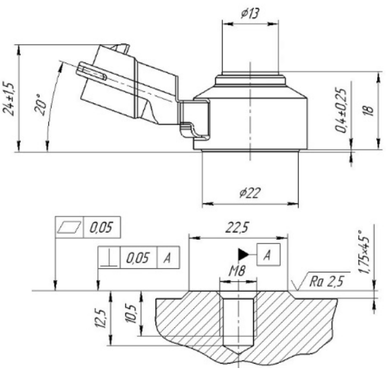

Fig. 6. Diagram and photo of the location of the knock sensor.

To record the signal from a piezoelectric pressure sensor, it is necessary to use a charge amplifier and an analog-to-digital converter (ADC) [43-45]. LE-41 was chosen as a charge amplifier, with the use of which measurements have already been carried out [46], showing a linear dependence of the measured charge on the magnitude of the dynamic load for different measurement frequencies. The calibration coefficients of the pressure sensor and channel LE-41 are as follows: sensor sensitivity 2.01 pC/bar; actual transmission coefficient 55.4 bar/V; coefficient taking into account the channel divider is 184.4 bar/V. The “Mobile complex for collecting and processing signals from an electronic internal combustion control system MDK-3.2” was selected as the measuring system, the software of which allows you to analyze the workflow and export data, and L-Card E-502 was used as an ADC, the characteristics of which are given in Table 4 [47].

Table 4. Characteristics of L-Card E-502 analog-to-digital converter.

Parameter name	Parameter value
Input voltage range	±10 V, ±5 V, ±2 ±10 V, ±1 V, ±0.5 V, ±0.2 V
Number of ADC channels	16/32
Operating temperature, °C	+5 ~ +40 (when operating the E-502 module without a housing, the upper limit of the operating temperature range is +50 °C)
USB 2.0 transfer speed (High Speed)	5 Motsch/s for input and output. (1 rep = 32 bits)
Input impedance	>10 Mohm (for single-channel input)
Input protection	±15 V
Maximum conversion frequency	2 MHz
ADC resolution, bit	16
Effective bit depth	14,5 bit (400 kHz, measuring range 2 V)
External power supply	12 V, not less than 0.5A
Overall dimensions, mm	140 x 112 x 39 (excluding cable parts of connectors)

The schematic diagram and composition of the experimental setup is shown in Figure 7.

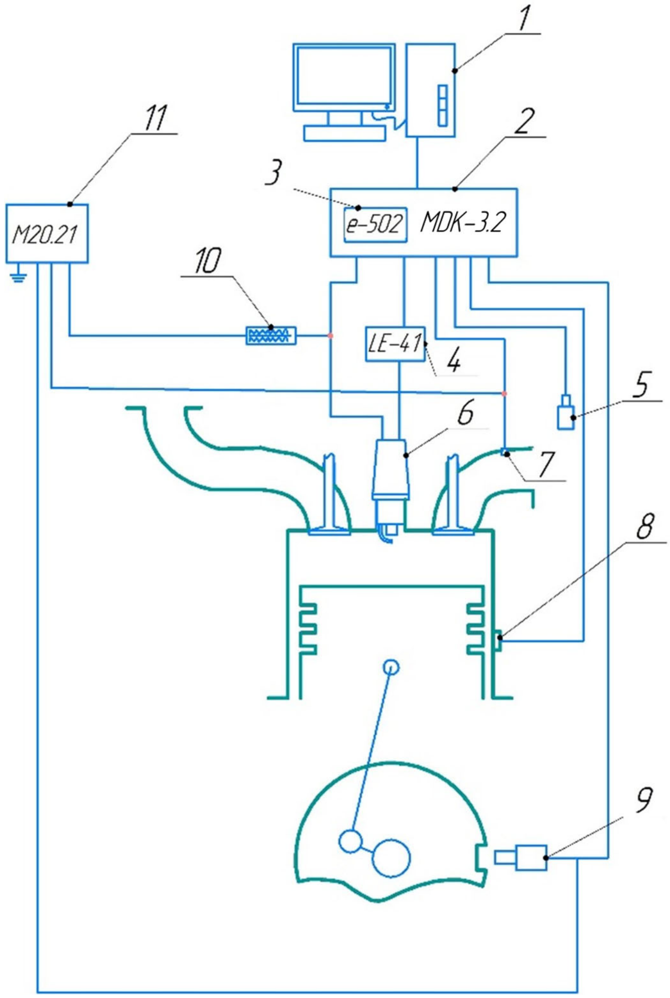

Fig. 7. Schematic diagram of the experimental setup: 1 – Personal computer (PC); 2 – Mobile complex for collecting and processing signals from the electronic internal combustion control system MDK-3.2; 3 – Analog-to-digital converter L-Card E-502; 4 – Charge amplifier LE-41; 5 – Lambda probe, oxygen sensor; 6 – spark plug with integrated pressure sensor; 7 – Intake manifold pressure sensor; 8 – Knock sensor; 9 – Crankshaft speed sensor; 10 – Ignition coil; 11 – ABIT M20.21 electronic control unit.

3 Results and discussion

Measurements were made of the engine operating process with ignition of the working air-methane mixture, under different acceleration modes without load with varying the moment of ignition of the mixture; as a result of preliminary processing of the measurement results (Figure 8), signs of normal (Figure 9) and detonation combustion (Figure 10) were found.

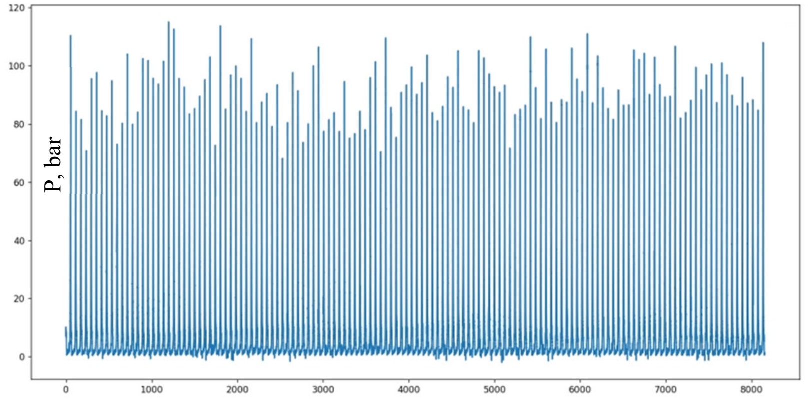

Fig 8. Fragment of an indication diagram when measuring pressure in a cylinder on a stationary installation (135 signals).

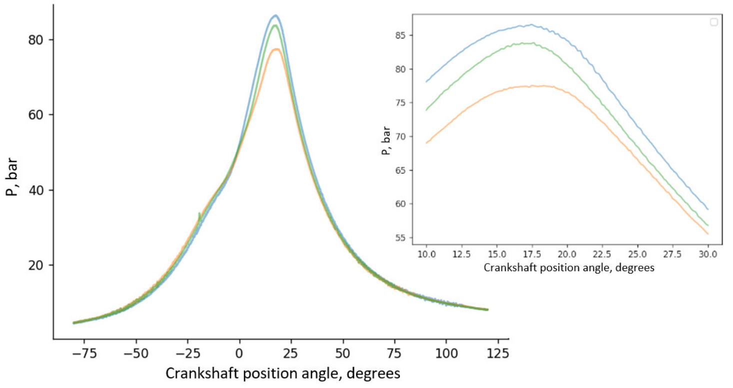

Fig. 9. Graph of pressure changes in the combustion chamber without detonation combustion.

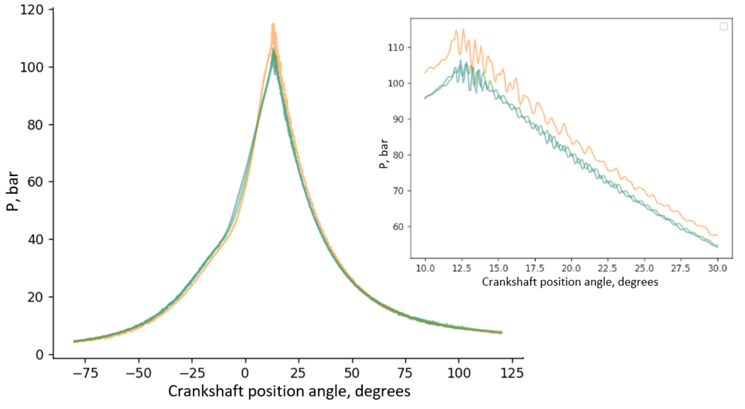

Fig. 10. Graph of pressure changes in the combustion chamber during detonation combustion.

For a detailed analysis of detonation combustion, it is necessary to further consider the influence of natural oscillations of the pressure sensor and the drift of the signal of the piezoelectric sensor [48], however, looking at the nature of the change in the curve shown in Figure 10, we can talk about fragments of detonation combustion.

It is known that the tendency for engines to detonate manifests itself in "wide open throttle" modes [49], and at partial loads under the conditions of the stationary stand used, the maximum temperature and cycle pressure are reduced and, as a result, the probability of detonation combustion is also reduced. It should be emphasized that experimental studies during actual operation are of particular importance, since the air temperature in the intake manifold after the air cooler can significantly exceed 25°C (up to 800°C), which increases the likelihood of detonation combustion [50]. In [51], it is theoretically shown that premature failure of KAMAZ 820 gas engines is associated with the detonation nature of combustion.

Thus, to identify possible detonation and the reasons for its occurrence during the combustion of compressed natural gas in the KAMAZ engine of the 820.60 series, it is necessary to study the data of long-term recording of detonation combustion events, which makes it possible to experimentally identify the dependence of the manifestation of detonation in the engine under study on the methane number of the fuel [52], composition fuel-air mixture [53], state of the ignition system [54], load, thermal state of the engine and other factors under vehicle operating conditions.

4 Conclusion

A stationary laboratory installation for studying the combustion process of methane fuel in the combustion chamber of a KAMAZ 820.60 series engine made it possible to measure the gas pressure in the engine cylinders as the most informative diagnostic parameter characterizing the condition of the engine piston part.

Processing and analysis of cylinder pressure measurement data made it possible to obtain information about the quality of the working processes of the engine under study and to evaluate the quality of adjustment.

The possibility of using on-board recording of detonation combustion events under real engine operation conditions and identifying factors influencing detonation combustion in the engine to quickly identify the causes of defects in the cylinder heads of the KAMAZ 820.60 series engine is shown.

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