Improvement of diagnostics of the cylinder-piston group of internal combustion engines

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Abstract. The paper considers the study of the dependence of the number of leaks of compressed air from the over-piston space of an internal combustion engine on the wear of its cylinder-piston group. To conduct this study, a special pneumatic tester was made that allows measuring leaks at pre-established characteristic points inside the cylinder liner. The most common engine operation malfunctions affecting the tightness of the combustion chamber were modeled. As a result of the study, the following patterns were revealed. With an increase in the ovality and taper of the worn sleeve of the KamAZ 740 engine, the readings of the pneumatic tester decrease from 4.2 kg/cm² to 3.4 kg/cm², when the rings are coked from 3.5 kg/cm² to 3 kg/cm², and when they break from 2 kg/cm² to 1.5 kg/cm². For the engine sleeve of the ZMZ 53, the readings of the pneumatic tester are reduced from 3.7 kg/cm² to 3.4 kg/cm², when the rings are coked from 3.3 kg/cm² to 3 kg/cm², and when they are broken from 1.8 kg/cm² to 1.35 kg/cm². When the valve leak increases from 10 mm² to 20 mm², the instrument reading drops sharply to 0.

1. Introduction
The main problem of the agro-industrial complex of the Russian Federation is that every year agricultural enterprises of the country spend up to 50 million rubles of the budget to maintain worn-out equipment in working condition, the percentage of wear and service life of more than 20 years of which is up to 70%. Such costs make up a significant part of the total gross agricultural product.

The relevance of the development of a new method for assessing the condition of the cylinder-piston group is due to the fact that, according to statistics, the main reason for setting the engine for repair is the state of its CPG (cylinder-piston group) and its failures [1,2]. According to the State Research Technological Institute for the Repair and Operation of Tractors and Agricultural Machinery of Russia, the wear rate of engines of the same brand entering into repair after one season can differ up to 20 times. Accordingly, knowing only the data on the operating time of the engine, it is impossible to judge the state of its CPG, and therefore make a decision on setting it up for repair or extending its service life. All this leads, in the end, to an excessive expenditure of spare parts, money and man-hours [3].

The current economic state of the agro-industrial complex shows that an extremely small number of farms are able, for lack of funds, to carry out timely repairs of cars in compliance with all regulated
norms. Often, repairs are not carried out until the equipment reaches the maximum wear conditions, which then leads to high costs of both labor intensity and spare parts.

The main engine unit that actually determines its resource is the cylinder-piston group. All this leads to the interest of agricultural enterprises in the possibility of obtaining modern diagnostic methods that allow timely determining and assigning the necessary measures of technical and service impact to ensure the most high-quality and durable operation of the machine [4]. As this method, it is proposed to develop differentiated methodology for assessing the condition of the sleeves by the method of pneumotesting.

The method of pneumotesting was developed at the end of the twentieth century and later on its basis were created various devices for assessing the state of CPG. In general, since its development, this technique has proven itself well and a large statistical base has been accumulated, but there is still no method by which it would be possible to accurately judge the wear of the cylinder liner without using other diagnostic methods [5].

Pneumatic methods to some extent simulate the operating conditions of the engine, since the working space above the piston is compacted. However, in the existing studies on pneumatic diagnostics of CPG, it is clear that these methods provide only a generalized assessment of the condition of the unit, without indicating specific malfunctions, the amount of wear and, often, do not provide information about the need for major repairs [6].

Of the pneumatic diagnostic methods, the method of pneumotesting is of the greatest interest. However, studies of this method do not reveal the theoretical regularities of the parameters recorded by it. All this provides a search for ways to improve the diagnosis of CPG of the internal combustion engine by this method. The purpose of our study is to determine the dependence of the amount of air leaks from the over-piston space on the amount of wear of the cylinder liner for further decision-making on the need to install the engine for repair.

2. Materials and methods
As an object of research to determine the ratio of loose coupling ‘sleeve-ring-piston’ during pneumatic testing, the sets of CPG engines ZMZ-53 (Zavolzhsky Motor Plant, Russia) and KamAZ 720 (Kama Automobile Plant, Russia). These sets belonged to the engines that were received for repair and, according to the results of defectation, were recognized as unfit for operation. For the study, several sets were selected with different types and degrees of wear. The study to determine the ratio of loose coupling ‘sleeve-ring-piston’ during pneumatic testing was carried out using a pneumatic tester (PN-1, Department of ‘Technical and Biological Systems’ of the State Educational Institution of Higher Education of the Russian Academy of Sciences, Russia).

According to the diagram shown in figure 1, the device works as follows: the air under the pressure created by the compressor (2) is supplied via a pneumatic line (7) to the regulator (3), which sets the set operating pressure of the \( P_{\text{tab}} \), which is maintained during the experiment. Then the air enters through the tap (6) into the over-piston space, where its pressure will depend on the amount of leaks through the ‘piston-cylinder-sleeve’ interface. This pressure is determined by the measuring pressure gauge (4) and the greater the amount of air leakage, the less it will be. To control the working and measuring pressure, pressure gauges of accuracy classes 3 and 5 are used, respectively. To purge the selected CPG sets, a specially manufactured device is used, as shown in figure 2.

The device consists of two covers, between which the tested CPG set is installed. The covers are tightened with four pins clamping the sleeve. To prevent air leaks from the over-piston space, a gasket is installed between the sleeve and the top cover. The piston is installed in five different positions to check for leaks in the CPG: UDC (upper dead center), when turning the crankshaft at 45°, 90°, 135° and in LDC (lower dead center). The piston is fixed by a special flange installed in the lower connecting rod head. The pneumatic characteristic is removed at 5 points corresponding to the rotation of the internal combustion engine crankshaft at an angle of 45°, 90°, 135°, as well as in UDC and LDC.
Before removing the characteristics, the selected CPG sets should be washed with diesel fuel mixed with oil in order to remove particles of combustion products and wear from the gaps in the ‘piston – ring – sleeve’ interface. After washing, the selected kit is installed in the experimental installation and the upper and lower covers are pressed against the upper end of the sleeve with the help of screeds. A rubber gasket is installed between the upper cover and the end of the sleeve to prevent air leaks. The tightness of the joint is controlled by wetting the point of their contact, if the liquid bubbles, it means that the connection is not tight. After the installation is assembled, compressed air is supplied under pressure through a fitting installed in the upper cover. The readings during the purge process are taken from the measuring pressure gauge installed on it. The purge of the installation begins with the position of the piston at the lower dead center, followed by moving it up and fixing it at the above points. The piston is fixed from moving by means of a specially made stopper.

Additionally, leak measurements are carried out at different positions of the piston rings: 1. the ring locks are separated by 180° relative to each other perpendicular to the axis of the piston pin; 2. the ring locks are located on the same axis; 3. the ring locks are placed randomly.

The readings of the pneumatic calibrator will be more accurate the better the fit of the rings on the lower plane of the piston grooves is ensured. To achieve this goal, the measurements were carried out at a relatively high air pressure entering the supra-piston space (5 kg/cm²). Also, during the experiment, the piston moved from the bottom up. Additionally, to simulate leaks in the cylinder during compression of the working fluid, as well as a better fit of the rings, an increased pressure of 7 kg/cm² was briefly applied to the cylinder, and then it was reduced to the working 5 kg/cm², and readings were taken. Additionally, for greater reliability of the results, compression measurements were performed at pressures reduced to 4 kg/cm² and increased to 6 kg/cm².

To obtain more reliable results, measurements of the leakiness of the supra-piston space by pneumatic testing should be performed three times, and the wear of this tribo-tension should be evaluated by the average values of the values obtained. It was found experimentally that the readings of the measuring pressure gauge can be affected by a change in the length of the hose from the compressed air source to the experimental installation, therefore, to avoid an error, all measurements were carried out using a hose of the same length.
According to the same method, the amount of leakage is fixed for all sets of CPG.

In order to identify the analytical relationships between the readings of the pneumatic tester and various types of cylinder malfunctions, it is necessary, in the course of the experiment, to simulate the most common malfunctions that occur during ordinary engine operation, which affect the tightness of the combustion chamber.

It is well known that the most common malfunctions of this type are: severe wear of the cylinder liner; coking of compression rings; jamming of compression rings; compression rings breakage; violation of the tightness of the valve mechanism; various malfunctions of the oil removal rings.

Before conducting the experiment, we will conduct a micrometer study of the CPG of the selected engine and measure the initial compression values. Micrometric measurements of the wear of the internal combustion engine liners were carried out at various positions of the crankshaft, namely in UDC, LDC and rotation angles of 45°, 90°, 135°. These measurements were carried out in 4 planes: the finger, the swing of the connecting rod and with an offset at an angle of 45° from them.

To determine the relationship between the readings of the pneumatic tester and the parameters of the extremely worn sleeve, replace one of the sleeves with this one. To simulate the failures associated with the jamming of the rings, manually jam the compression rings by gluing them into the groove on one side of the lock according to the figure 3.

To simulate the failure of the rings, remove them. To simulate the looseness of the timing valve mechanism, we will move the rocker arm adjustment screw. The dependence of the value of the intake valve lift on the area of the flow section changes according to the following law [7, 8]:

$$h_{ii} = \frac{f_{ii}}{\frac{\pi}{2} (d_2 \cos \alpha + h_{0i} \sin \alpha \cos \alpha)}$$

(1)

where, $h_{ii}$ – valve lifting height, mm; $f_{ii}$ – the area of the flow section of the valve, mm; $d_2$ – valve neck diameter, mm; $\alpha$ – angle of inclination of the valve chamfer, deg.

After performing the calculations, we will plot the dependence of the amount of the intake valve lift on the area of the flow section.

According to this schedule, we will select the amount of the required movement of the valve to ensure the desired leakiness. The movement of the valve is provided by simply screwing in the adjusting screw of the rocker arm of the engine's gas distribution mechanism [9, 10].
The information was formed on the basis of the results of diagnostics by pneumatic testing of 300 cylinder-piston groups of engines carried out in the conditions of service stations and various repair enterprises. According to the data obtained, it was possible to establish that out of the entire mass of internal combustion engine malfunctions, piston ring malfunctions account for 56%, cylinder liner malfunctions – 20%, gas distribution mechanism malfunctions – 11%, and 13% – other malfunctions. The reliability of the diagnosis was confirmed by direct disassembly of the engine, endoscopy of the supra-piston space, and repeated diagnosis after the use of cleaning agents for CPG.

3. Results
We will measure the indicators with a pneumatic tester. In both cases, compressed air was supplied to the cylinders at a pressure of 6 kg/cm². The results of the measurements are presented in Table 1.

Table 1. Results of measurements of the parameters of the KamAZ 740 sleeve/ ZMZ sleeve 53.

| Crank mechanism position, degree of rotation of the crankshaft | Pressure gauge readings of the pneumatic tester, kg/cm² |
|------------------|---------------------------------------------|
|                  | 1    | 2    | 3    | 4    |
| UDC 0°           | 3.4/3.9 | 3    | 1.5  | 3.4/3.9 |
| 45°              | 3.7/3.8 | 3.1  | 1.7  | 3.7/3.8 |
| 90°              | 3.8/3.65 | 3.2  | 1.8  | 3.8/3.65 |
| 135°             | 4/3.55 | 3.3  | 1.9  | 4/3.55 |
| LDC 180°         | 4.2/3.5 | 3.5  | 2    | 4.2/3.5 |

Number 1 in the table shows the results for a worn sleeve with working compression rings. Under the number 2 with the introduced fault in the form of coking compression rings. Under the number 3 with the introduced fault in the form of broken rings. Under the number 4 with the introduced fault in the form of a breakdown of the oil removal rings.

In addition to the considered malfunctions, in the ordinary operation of engines, the so-called pumping effect of rings is sometimes observed, when oil enters the over-piston space of the internal...
combustion engine. Also, oil ingress can occur due to wear of the timing valve guide bushings and leakage of the turbocharger shaft seals.

To simulate and model the ingress of oil into the over-piston space, 25 mg of engine oil was added to the sleeve, preheated to the operating temperature. Accordingly, after purging the sleeve with this introduced fault, the following readings of the device were obtained.

Table 2. The result of the experiment with the ingress of oil into the over-piston space of the KamAZ 740/ZMZ 53 sleeve.

| CM position, degree of rotation of the crankshaft | Pressure gauge readings of the pneumatic tester, kg/cm² |
|-----------------------------------------------|-----------------------------------------------------|
| UDC 0⁰                                          | 4/3.9                                                |
| 45⁰                                            | 4/1.4                                                |
| 90⁰                                            | 4.2/4                                                |
| 135⁰                                           | 4.3/4.1                                              |
| LDC 180⁰                                       | 4.5/4.2                                              |

The experiment on the introduction of malfunctions showed that with an increase in the ovality and taper of the worn sleeve of the KamAZ 740 engine, the readings of the pneumatic tester decrease from 4.2 kg/cm² to 3.4 kg/cm², when the rings are coked from 3.5 kg/cm² to 3 kg/cm², and when they break from 2 kg/cm² to 1.5 kg/cm². For the engine sleeve of the ZMZ 53, the readings of the pneumatic tester are reduced from 3.7 kg/cm² to 3.4 kg/cm², when the rings are coked from 3.3 kg/cm² to 3 kg/cm², and when they are broken from 1.8 kg/cm² to 1.35 kg/cm².

The influence of an excessive amount of oil in the over-piston space on the increase in the readings of the pneumatic tester was also confirmed. Based on table 2, it can be seen that they increased for the KamAZ engine from 4.5 kg/cm² to 4 kg/cm², and for the ZMZ 53 engine from 4.2 kg/cm² to 3.9 kg/cm².

In addition to the faults described above, the value of the timing valve leakage was also modeled by increasing the value of its opening by hкл. To do this, the test sleeves were installed on engines with working cylinder heads. According to studies, the value of the valve leakage in the course of ordinary operation varies from 0 to 4 mm². But, as you know, damage and burnout increase this value much more. The value of the valve displacement was set in accordance with the dependence shown in figure 4. The data obtained for valve leaks are shown in the table 3 below.

Table 3. Indications for the KamAZ 740/ZMZ 53 engine.

| Valve leakage value, mm² | Pneumatic tester reading, kg/cm² |
|--------------------------|----------------------------------|
| 3                        | 4.2/3.7                          |
| 10                       | 1.9/1.7                          |
| 20                       | 0                                |

After conducting the experiment, we see that with a valve leak in the size of 3 mm², the value of the pneumatic tester readings practically does not differ from its value with the wear of the rings, therefore, with such small values of the leak, it is almost impossible to recognize the burnout of the valve at this stage without using other diagnostic methods.

It is also found that with an increase in the valve leakage from 10 mm² to 20 mm², the readings of the device are sharply reduced to zero. In accordance with the research methodology, the cartridge cases of KamAZ 740 and ZMZ 53 were purged using the assembled unit. In order to obtain more reliable data on the dependence of the pneumatic tester readings on the wear of the engine sleeve, the experiment was carried out on a specially made laboratory installation. The results of the experiment are presented in the table 4 below.
Table 4. Readings of the device in the sleeve of the KamAZ 740/ZMZ-53.

| CM position | Instrument readings, MPa | Lock position |
|-------------|--------------------------|---------------|
|             | 6·10^5                   | 5·10^5        | 4·10^5        |
| 0° (UDC)    | 3.1/3.8                  | 2/2.9         | 1.7/2.2       |
| 45°         | 3.5/3.7                  | 2.1/2.7       | 1.7/2.1       |
| 90°         | 3.6                      | 2.4/2.6       | 2             |
| 135°        | 3.8/3.55                 | 2.6/2.55      | 2.1/1.8       |
| 180° (LDC)  | 3.9/3.5                  | 2.8/2.5       | 2.3/1.6       |

| CM position | Instrument readings, MPa | Lock position |
|-------------|--------------------------|---------------|
|             | 6·10^5                   | 5·10^5        | 4·10^5        |
| 0° (UDC)    | 3.4/3.9                  | 2.8/3.5       | 1.9/2.7       |
| 45°         | 3.6/3.9                  | 2.9/3.1       | 1.9/2.6       |
| 90°         | 3.7                      | 3/2.8         | 2/2.4         |
| 135°        | 4.1/3.6                  | 3.5/2.6       | 2.5/2.2       |
| 180° (LDC)  | 4.3/3.55                 | 3.6/2.55      | 2.7/2.1       |

According to the data obtained by us, the dependence of the readings of the $P_c$ pneumatic tester on the amount of sleeve wear is approximated by the following expressions (W - wear): for the rolling plane of the connecting rod at an operating pressure of 6 kg/cm$^2$ (2):

$$ W = \frac{12.5 - P_c}{48} $$

(2)

for the rolling plane of the connecting rod at an operating pressure of 5 kg/cm$^2$ (3):

$$ W = \frac{23 - P_c}{48} $$

(3)

for the rolling plane of the connecting rod at an operating pressure of 4 kg/cm$^2$ (4):

$$ W = \frac{17.3 - P_c}{36} $$

(4)

for the plane of the piston pin at an operating pressure of 6 kg/cm$^2$ (5):

$$ W = \frac{12.3 - P_c}{21} $$

(5)

for the plane of the piston pin at an operating pressure of 5 kg/cm$^2$ (6):

$$ W = \frac{22.5 - P_c}{48} $$

(6)

for the plane of the piston pin at an operating pressure of 4 kg/cm$^2$ (7):
4. Conclusion

All of the above allows us to draw the following conclusions. When the valve is loose in the size of 3 mm², the value of the pneumatic tester readings practically does not differ from its value when the rings are worn, therefore, with such small values of the leak, it is almost impossible to recognize the burnout of the valve at this stage without using other diagnostic methods.

With an increase in the ovality and taper of the worn sleeve of the KamAZ 740 engine, the readings of the pneumatic tester decrease from 4.2 kg/cm² to 3.4 kg/cm², when the rings are coked from 3.5 kg/cm² to 3 kg/cm², and when they break from 2 kg/cm² to 1.5 kg/cm². For the engine sleeve of the ZMZ 53, the readings of the pneumatic tester are reduced from 3.7 kg/cm² to 3.4 kg/cm², when the rings are coked from 3.3 kg/cm² to 3 kg/cm², and when they are broken from 1.8 kg/cm² to 1.35 kg/cm².

When the valve leak increases from 10 mm² to 20 mm², the instrument reading drops sharply to 0.

After analyzing the typical cases of malfunctions, it can be concluded that compression in diesel engines less than 15-17 kg/cm² indicates cracks or breakage of the piston rings, and for gasoline engines this indicator corresponds to 7-8 kg/cm². As for the oil removal rings, the analysis conducted indicates coking, wear and breakage at compression rates for diesels of 25 kg/cm² or more and 12.5 kg/cm² for gasoline engines.

The method described above is suitable for conducting non-selective diagnostics of engines and other brands, taking into account certain clarifying adjustments.

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