1. INTRODUCTION

One of the main tasks of modern engine building is to improve the operational and environmental performance of internal combustion engines (ICEs) [1-7]. Due to the increased number of motor vehicles, the share of oil fuel consumption is constantly growing. Along with the increasing number of electric vehicles, ICEs are still the basis of the world transport fleet [8]. Until a complete transition to electric transport, considerable attention should be paid to monitoring the environmental parameters of ICEs [9-11].

Along with the development of fundamentally new ICE models, which require complex long-term studies and significant capital investments, it is essential to improve the existing ICEs and their diagnosing methods [12].

The main works of the leading scientists in the field of transport ecology are aimed at the development of new devices for the neutralization of exhaust emissions, systems for monitoring the parameters of exhaust toxicity, as well as selective adjustment of fuel supply when the technical condition of ICE systems changes [13-16]. The effectiveness of these solutions has been proven during the operation of completely new vehicle systems having no running time [17-20]. Ideal conditions for the operation of vehicles were in these studies. However, the realities of operation show that, in most cases, car owners, car fleets, and automobile enterprises are unable to provide ideal conditions for the operation of ICE systems having no running time [17-20].

The lack of diagnostic tools that reliably determine the factors affecting the environmental performance of ICEs leads to high costs for detecting the troubleshooting (about 3000...7000 troubles per car). Based on the analysis of the existing methods for assessing the factors affecting the environmental performance of ICEs and the wear of the main ICE systems, we can conclude that such elements as the cylinder-piston group (CPG) are a rather reliable system, and the CPG wear factor can be neglected. However, at the same time, we should have a
way to control the technical condition of the CPG, preferably integrated into the ICE control system to be able to control the CPG at any time. An analysis of ICE element failures shows that the maximum number of them falls at electromagnetic nozzles, spark plugs, and the exhaust catalytic converter. Besides, these elements significantly affect the environmental performance of ICEs [30-32].

Given the aforesaid and according to the set purpose, we identified the following research tasks.

1. To identify the relationship between the technical condition of ICE elements and the toxicity parameters.
2. To develop a method for assessing the technical condition of electromagnetic nozzles, spark plugs, and exhaust catalytic converters by the toxicity parameters during selective exhaust gas sampling.
3. To develop diagnostic equipment and experimentally establish diagnostic test modes and control parameters to study the technical condition of ICE systems.
4. To justify the diagnostic method using the developed equipment, carry out comparative studies and show their effectiveness.

3. RESEARCH PROCEDURE

In the course of the experimental studies, the input parameters are: 1) the spark gap of the spark plug; 2) the change in the capacity of the electromagnetic nozzle; 3) the resistance of the catalytic converter. The controlled parameters include the temperature of the ICE coolant, the technical condition of the cylinder-piston group (CPG), the gas distribution mechanism (GDM), the oil temperature. The output parameters include the ICE crankshaft, CO, CO₂, CH, O₂. After that, the data was processed in the SigmaPlot software suite, the verification and comparative studies were carried out with the use of Excel and Mathcad.

As we can see from the graph in Fig. 1, the nature of the change in the concentration of CO₂ and NOₓ in the exhaust gases is rather similar. When the engine operates in the rich mixture zone at \( \alpha = 0.55...0.9 \), the concentration of CO₂ increases almost linearly from 4 to more than 11%. At the same time, the concentration of NOₓ in the same range increases from 0 to 0.42%. The law of the change in the concentration of NOₓ can be almost taken as linear in this section. Next, we can see from Fig. 1 the maximum concentration of CO₂ and NOₓ actually coinciding at \( \alpha = 1.02...1.05 \).

Then, at \( \alpha > 1.05...1.10 \) the formation of NOₓ decreases, which is connected with a decrease in the combustion temperature. The nature of the change in CO₂ and NOₓ also remains the same in this range. Thus, we can indirectly judge on the value of NOₓ by the value of the concentration of CO₂, with a good approximation. Notably, the given research material did not set the task to determine the dependence of NOₓ, but in our future work we will use a gas analyzer enabling to measure NOₓ.

To study the relationship between the spark gap of the spark plug and the ionization voltage, we studied this process. To this end, we artificially set the gaps of 0.5, 0.7 and 1.4 mm. At the same time, the air density in the chamber of the test device changed from 7 to 20 kg/m³. After that, we monitored the change in the increment of the secondary voltage \( dU2/dt \), V/s (Fig. 2).

![Figure 1. A dependence of the concentration of CO, CH, CO₂ and NOₓ on \( \alpha \)](image)

![Figure 2. The dependence of the increment of the secondary voltage \( dU2/dt \) (V/s) on the air density in the chamber of the test device \( \rho \) (kg/m³) for various gaps in the spark plug](image)
Figure 3. The dependence of the breakdown voltage $U_{br}$ (kV) on the air density in the chamber of the test device $\rho$ (kg/m$^3$) at various values of the secondary voltage increment $dU_2/dt$ (V/s)

The analytical studies allowed us to establish that the limit value of the spark plug gap is a gap of 1.1 mm upwards and 0.3 mm downwards.

A joint analysis of the preliminary experiments on studying the relationship between the spark gap of the spark plug, the change in the capacity of the electromagnetic nozzle, and the resistance of the catalytic converter with the exhaust toxicity parameters showed their significant relationship. These studies allowed us to create a generalized mathematical model taking into account the composition of the exhaust gases to the catalytic converter with the technical condition of the spark plugs, electromagnetic nozzles, and the catalytic converter. All research results were summarized in a series of functional dependencies:

$$n = f(Z, F, R). \quad \ldots \quad (3)$$

$$O_2 = f(Z, F, R). \quad \ldots \quad (4)$$

$$CH = f(Z, F, R). \quad \ldots \quad (5)$$

$$CO = f(Z, F, R). \quad \ldots \quad (6)$$

$$CO_2 = f(Z, F, R). \quad \ldots \quad (7)$$

where $n$ is the crankshaft speed of the internal combustion engine, rpm; $O_2$ is the oxygen content in the exhaust gases, %; $CH$ is the hydrocarbon content, ppm; $CO$ is the carbon monoxide content, %; $CO_2$ is the carbon dioxide content in the exhaust gases, %; $Z$ is the spark plug gap, mm; $F$ is the capacity of the electromagnetic nozzle, %; $R$ is the equivalent resistance of the converter, mm.

The data was processed using the MatlabSimulink software suite. The calculation model is presented in Fig. 4.

When processing the data in the MatlabSimulink software, we obtained the dependencies of various output parameters on the combination of three input parameters. So, Fig. 5 and Fig. 6 present the dependence of the concentration of $CO_2$ (%) in the exhaust gases on the equivalent resistance of the catalytic converter $R$ (mm), the capacity of the electromagnetic nozzle $F$ (%), and the spark plug gap $Z$ (mm).

Figure 5. The dependence of the concentration of $CO_2$ (%) in the exhaust gases on the equivalent resistance of the catalytic converter $R=10$ mm, the capacity of the electromagnetic nozzle $F=94\%$ and the spark plug gap $Z=0.3$ mm.

Figure 6. The dependence of the concentration of $CO_2$ (%) in the exhaust gases on the equivalent resistance of the catalytic converter $R=34$ mm, the capacity of the electromagnetic nozzle $F=106\%$ and the spark plug gap $Z=1.1$ mm.

We can see from Fig. 5 and Fig. 6 that the concentration of $CO_2$ increases with a decrease in the equivalent resistance of the catalytic converter from 10 to 34 mm in the catalytic converter. The concentration of $CO_2$ decreases sharply with an increase in the capacity of the electromagnetic nozzles from 94 to 106%. The concentration of $CO_2$ increases with an increase in the spark plug gap from 0.3 to 1.1 mm.

A failure analysis of automotive catalytic converters shows that when their cross-section is reduced, cleaning of the working cylinders is significantly impaired. This causes the accumulation of exhaust gases and their return into the combustion chamber through the exhaust system, which results in an increased content of $CO$, $CH$, interrupted the mixture ignition, excessive fuel consumption, and a significant power loss. An increase in the capacity of the electromagnetic nozzles causes an over-enrichment of the fuel and, as a consequence, worsened fuel combustion and an increase in $CO$ and
data for the calculation. It is well known that our experimental setup based on the ICE of a VAZ-2112 car has a compression ratio of $\varepsilon = 1.1$. During the experiments, we used A-92 gasoline. Besides, the average elemental composition and molecular weight of A-92 gasoline was: carbon $C = 0.855$; hydrogen $H = 0.145$; molecular weight $m_T = 115$ kg/kmol. The lower heating value of A-92 gasoline can be calculated by Eq. (8):

$$H_u = 33.9IC + 125.6H - 10.89(O - S) - 2.5l(9H + w).$$ (8)

The theoretical amount of air needed to combust 1 kg of fuel is determined by Eq. (9-10):

$$L_0 = \frac{1}{0.208} \left( \frac{C}{12} + \frac{H}{4} + \frac{S}{32} - \frac{O}{32} \right).$$ (9)

$$l_0 = \frac{1}{0.23} \left( \frac{8}{3} C + 8H - O \right).$$ (10)

The excess air ratio is determined based on the following considerations. An injection engine power supply system is installed on modern engines, [30, 31, 32]. The usability of the injection supply system for the designed engine allows us to obtain, provided that an appropriate adjustment is used, both the power and the economic mixture $\alpha = 0.7...1.3$ according to the assignment.

The amount of the combustible mixture at $\alpha=0.95$ is determined by Eq. (11):

$$M_1 = \alpha \cdot L_0 + \frac{1}{m_T}.$$ (11)

The number of individual components of complete combustion products at $K=0.5$ and the adopted speed mode:

$$M_{CO_2} = \frac{C}{12} + 2 \left( 1 - \frac{\alpha}{1 + K} \right) 0.208 \cdot L_0.$$ (12)

$$M_{CO} = 2 \left( 1 - \frac{\alpha}{1 + K} \right) 0.208 \cdot L_0.$$ (13)

$$M_{H_2O} = \frac{H}{12} - 2 \cdot K \left( 1 - \frac{\alpha}{1 + K} \right) 0.208 \cdot L_0.$$ (14)

$$M_H = 2 \cdot K \left( 1 - \frac{\alpha}{1 + K} \right) 0.208 \cdot L_0.$$ (15)

$$M_{N_2} = 0.792 \cdot \alpha \cdot L_0.$$ (16)

$$M_2 = M_{CO_2} + M_{CO} + M_{H_2O} + M_H + M_{N_2}.$$ (17)

Since the excess air ratio for the desired ICE varies within 0.7-1.3, substituting these values with an increment of 0.05 into Eqs. (12-17), we obtain the following dependecies (Fig. 9).

We can see from the analysis of Fig.9 that with an increase in the excess air ratio $\alpha$, the consumption of the combustible mixture increases, and the emissions of $CO_2$ and $H_2O$ increase slightly. The emissions of $NO_x$ also increase due to a larger amount of free oxygen and an increased fuel combustion temperature, which results in the increase in the amount of molecular oxygen.
Figure 9. The dependence of the number of individual components of complete combustion products $M$ on the excess air ratio $\alpha$

Here, we presented a generalized calculation of the largest possible number of components of exhaust gases based on the main, well-known models from the course of ICE calculation and combustion process chemistry. Although in the next work, the concentration of NO is controlled indirectly by the content of CO. As we can see from Fig. 9, in the rich mixture zone at $\alpha = 0.7...0.9$, we should steadily increase the amount of the combustible mixture to maintain the combustion process, while it can be seen that the total number of complete combustion products and the amount of $N_2$ sharply increase. In the poor mixture zone at $\alpha > 1.05...1.30$, these parameters grow with the same dynamics. At the same time, the dynamics of an increasing concentration of CO and $H_2O$ is very low throughout the change in the excess air ratio $\alpha$. Meanwhile, in the rich mixture zone at $\alpha = 0.7...0.9$, the amount of $H_2$ and CO changes insignificantly. In the poor mixture zone at $\alpha > 1.05...1.30$, the amount of $H_2$ and CO decreases dynamically. This is explained by better combustion completeness.

5. CHOOSING THE RESEARCH METHODOLOGY

We developed a research methodology to carry out all the planned complex works. It included the following steps: 1. To select the necessary experimental setup; 2. To select the necessary equipment and additional control devices; 3. To select diagnostic modes and diagnostic parameters. We opted for the VAZ-2112 ICE as the most common in the Russian Federation. The experimental setup and additional devices are shown in Fig. 10 and Fig. 11.

Besides, we selected the following main equipment: DBD-4 gasoline engine loader and INFRAKARM2.01 4-component gas analyser. Additional control devices were needed to control the secondary parameters of the ICE systems [17, 18]. The additional control devices include a MT-10 motor tester and a PC.

Figure 10. Experimental setup.

Figure 11. Equipment and additional control devices.

In the exhaust system, exhaust gas intake points are shown in individual exhaust manifolds. Holes were drilled at these points and nuts with adapters were installed to connect the gas analyser probe to them. Notably, this connection is made through a cooling coil to cool the exhaust gas before the gas analyser [33, 34, 35].

A $\lambda$-probe is shown further along the exhaust system. The catalytic converter and silencer come next. Special washers are installed at the end of the silencer to generate artificial resistance. The wires of the DBD-4 device are connected to the gap of the electromagnetic nozzles. DBD-4 is also connected to the control unit (ECU) of the ICE.

6. THE RESULTS OF THE EXPERIMENTAL STUDIES

Further tests were focused on comparing different exhaust gas intake options. To this end, we used an experimental setup based on the VAZ-2112 ICE (Fig. 10). The concentrations of CO, CH, CO$_2$, and O$_2$ were measured in three different ways: 1) the operation of the 1st cylinder and the exhaust gas intake in the common exhaust pipe; 2) the operation of all the four cylinders and the exhaust gas intake in the common exhaust pipe; 3) the operation of the 1st cylinder and the exhaust gas intake in the exhaust manifold immediately after the exhaust gases leave the cylinder. The measurements were carried out with a resolution of 500 rpm, starting at 1000 rpm.

As a result, we obtained the dependence of the concentration of CO (%) in the exhaust gases on the ICE crankshaft speed $n$ (rpm) (Fig. 11). The load level when one cylinder is on corresponds to 0.25 of the rated power at nominal crankshaft speeds. All the intermediate load values were determined using a tester motor. The parameter - ICE power during testing was displayed in its standard parameters.
As we can see from Fig. 11, during the operation of all the four cylinders and the exhaust gas intake in the common exhaust pipe, the concentration of CO in the exhaust gases reaches the highest values from 9.4 to 10.2%. The maximum is manifested at a point corresponding to 4,000 rpm. During the operation of the 1st cylinder and the exhaust gas intake in the exhaust manifold, immediately after the exhaust gases leave the cylinder, the concentration of CO reaches its maximum value of 4% at 1000 rpm. With an increase in the speed, the concentration of CO decreases, reaching 1% at 5000 rpm. During the operation of the 1st cylinder and the exhaust gas intake in the common exhaust pipe, the concentration of CO reaches its minimum value of 1.98% at 1000 rpm. Further, the concentration of CO is kept at a level of no more than 1% with an increase in the ICE crankshaft speed. However, this low CO value is explained by the mixing of free air entering the outlet from neighbouring idle cylinders.

Figure 11. The dependence of the concentration of CO in the exhaust gases on the ICE crankshaft speed \( n \) during the operation of different cylinders

An analysis in Fig. 12 shows that CH reaches significantly higher values during the operation of all the four cylinders and the exhaust gas intake in the common exhaust pipe. So at 1,000 rpm, the concentration of CH reaches a maximum of 715 ppm. Further, with an increase in the ICE crankshaft speed, CH decreases and amounts to 400 ppm at 5000 rpm. During the operation of the 1st cylinder and the exhaust gas intake in the common exhaust pipe and the operation of the 1st cylinder and the exhaust gas intake in the exhaust manifold immediately after the exhaust gases leave the cylinder, we observe almost identical results varying within the experimental error.

An analysis of the data in Fig. 13 shows that the highest value of the concentration of CO\(_2\) is observed during the operation of the 1st cylinder and the exhaust gas intake in the exhaust manifold immediately after the exhaust gases leave the cylinder. So, at the ICE crankshaft speed of 1,000 rpm, the concentration of CO\(_2\) is 10.7%. Then, the concentration of CO\(_2\) grows and reaches a maximum of 14% at the ICE crankshaft speed of 4,500 rpm. During the operation of all the four cylinders and the exhaust gas intake, a slightly lower CO\(_2\) value is observed in the common exhaust pipe. This is explained by free oxygen coming from the neighbouring cylinders in the absence of combustion in them. The lowest CO\(_2\) value is observed during the operation of the 1st cylinder and the exhaust gas intake in the common exhaust pipe. Free oxygen from the neighbouring cylinders also has a significant effect in the absence of combustion in them.

Figure 12. The dependence of the concentration of CH in the exhaust gases on the ICE crankshaft speed \( n \) during the operation of different cylinders

Figure 13. The dependence of the concentration of CO\(_2\) in the exhaust gases on the ICE crankshaft speed \( n \) during the operation of different cylinders
Based on the results of the experiment, we built the dependence of the concentration of $O_2$ (%) in the exhaust gases on the ICE crankshaft speed $n$ (rpm) (Fig. 14).

![Figure 14. The dependence of the concentration of $O_2$ in the exhaust gases on the ICE crankshaft speed $n$ during the operation of different cylinders.](image)

Analysing Fig. 14, we can see that the concentration of $O_2$ reaches its maximum values during the operation of the 1st cylinder and the exhaust gas intake in the common exhaust pipe. We can see that the concentration of $O_2$ is on average 16.2%, whereas the concentration of $O_2$ is below 2% during the operation of the 1st cylinder and the exhaust gas intake in the exhaust manifold immediately after the exhaust gases leave the cylinder. This is also explained by the impact of free oxygen from the neighbouring cylinders on the control result.

7. OPERATIONAL TESTS

As a result of the operational tests, we obtained comparative nomograms for determining the technical condition of the electromagnetic nozzles, the catalytic converter and the spark plugs of VAZ cars according to the results of analysing the exhaust gas composition. The maximum value of the upward or downward change in the registered parameter was taken for 100%. Zero value is taken at the reference condition of the elements specified by the manufacturer. It is convenient to consider the relative values of the parameters in %. The following parameters were controlled at the output: CO content, $CO_2$ content, $CH$ content, $O_2$ content, and the ICE crankshaft speed $n$. These parameters are measured by different values, but it is very convenient to compare them in % (Fig. 15).

We can see from Fig. 15 that the parameters $CH$ and $O_2$ take the maximum change. The concentration of $CH$ increases significantly with an increase in the capacity of the electromagnetic nozzle. The concentration of $O_2$, on the contrary, decreases significantly with an increase in the capacity of the electromagnetic nozzle.

![Figure 15. The complex dependence of the relative values of the controlled parameters of the content of CO, $CO_2$, CH, $O_2$, and the ICE crankshaft speed $n$ on the capacity of the electromagnetic nozzle $F$ (for VAZ ICE).](image)

The ICE crankshaft speed increases almost linearly with an increase in the capacity of the electromagnetic nozzle. The parameters $CO$ and $CO_2$ begin to increase significantly with a change in $F$ from 100 to 106%, with an entry of the rich air-fuel mixture.

Let us consider the complex dependence of the relative values of the controlled parameters of the CO content, $CO_2$ content, $CH$ content, $O_2$ content, and the ICE crankshaft speed $n$ on the spark plug gap $Z$ (mm) (for VAZ ICE) (Fig. 16).

![Figure 16. The complex dependence of the relative values of the controlled parameters of the content of CO, $CO_2$, CH, $O_2$, and the ICE crankshaft speed $n$ on the spark plug gap $Z$ (for VAZ ICE).](image)

An analysis of Fig. 16 shows that the parameters $CH$ and the ICE crankshaft speed reach the maximum changes. At the same time, the parameters $CH$ and $n$ sharply increase to $Z=0.8$ mm with an increase in the spark plug gap.

The values of $CO$ and $O_2$ grow with an increase in $Z$, but at $Z=0.8$ mm, the growth slows down.

We should say that varying the spark plug gap did not show the expected result. This particularly concerns the placement of gaps less than 0.6 mm. We observed a tendency that with an increase in the temperature of the
exhaust manifold, the concentration of CH decreased markedly. The values of the concentration of CH presented in Fig. 16 also varied from 0 to 30-40 ppm. That is, these changes were too close to the error margin of the gas analyzer and the imposition of other external factors.

Let us consider the complex dependence of the relative values of the controlled parameters of the CO content, CO\textsubscript{2} content, CH content, O\textsubscript{2} content, and the ICE crankshaft speed n on the equivalent resistance of the catalytic converter R (mm) (for VAZ ICE) (Fig. 17).

![Figure 17. The complex dependence of the relative values of the controlled parameters of the content of CO, CO\textsubscript{2}, CH, O\textsubscript{2} and the ICE crankshaft speed n on the equivalent resistance of the catalytic converter R (mm) (for VAZ ICE)](image)

An analysis of Fig. 17 shows that the parameters CO and n change to the maximum extent. The concentration of CO increases with an increase in the equivalent resistance of the catalytic converter. At the same time, the value of n, on the contrary, drops sharply with an increase in the equivalent resistance of the catalytic converter.

The parameters CH, CO\textsubscript{2} and O\textsubscript{2} will not change so noticeably, but they have obvious maximums and minimums within R=22 mm.

8. CONCLUSION

The state analysis showed that the dominating number of failures falls at the ICE: the ignition system -15-25%, the power system - 30-44%, the exhaust system - 10-15%. The creation and implementation of methods and tools for test diagnosing of the electromagnetic nozzle, the catalytic converter, and spark plugs allow us to get the annual savings of funds on one diagnostic station in the range of 699,700-855,200 rubles.

ACKNOWLEDGMENT

The work was supported by Act 211 Government of the Russian Federation, contract № 02.A03.21.

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Контрола животне средине и испитивање динамике контроле излазних параметара мотора

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Контрола животне средине има кључну улогу у модерном транспортној индустрији. У односу на одређене аспекти управљања компанија, укључујући моторе, моторне генераторе, даље ретакционарне агрегате и друге елементе, биле су уведене стандарде ЕУРО и ЕУРО 6. Због тога, у развоју улага се и многе друге стандарде и технички стандардизовани стандардизовани стандарди. Истовремено, управљање емисијом из моторних уређаја на свету је било и је осећање у англосаксонском региону због којег је се увогањем стандарда ЕУРО 6, ЕУРО 5 и ЕУРО 4 узрачунавајући емисије у еколошком осцилатору.
Постоји довољан број параметара, режима рада и додатних контролних уређаја за ову намену. У раду је приказан нови метод селективне контроле издувних гасова у сваком цилиндру. Праћени су следећи параметри: брзина брегасте осовине, потпуно и делимично исklучивање цилиндра (циклус по циклус), $O_2$, $CO$, $CO_2$ и $CH$. Режим рада је обезбеђен бројем исklучених завршених циклуса и брзином брегасте осовине. Контрола је изведена унутрашњим прилагођавањем довода горива под утицајем времена трајања убризгавања помоћу електромагнетне бризгаљке. Одређене су минималне вредности параметара токсичности издувних гасова за време трајања испитивања. Метод који објединjuје режиме рада и параметре омогућава смањење токсичности издувних гасова и побољшава степен искоришћености и учинак возила.