V. Shepelev

PhD
South Ural State University
Automobile and Tractor Faculty
Russia

A. Gritsenko

Doctor
South Ural State University
Automobile and Tractor Faculty
Russia
South Ural State Agrarian University
Russia

G. Salimonenko

PhD student
South Ural State University
Automobile and Tractor Faculty
Russia

Control of Hydrocarbon Emissions when Changing the Technical Condition of the Exhaust System of Modern Cars

The most applicable ICE monitoring method is selective control followed by individual corrections for the current technical condition. The combi–nation of a gas analyzer installed individually in each collector, a motor tester, and a loader which provides test modes makes it possible to recognize failures of exhaust and other systems with high accuracy and to assign an individual corrective action to ensure specified environmental and economic parameters. We developed a generalized mathematical model of changes in the composition of exhaust gases depending on changes in the resistance of the catalytic converter, the spark gap of the spark plug, and the capacity of the electromagnetic nozzle.

Keywords: control, diagnostics, gas analyzer, internal combustion engine, catalytic converter.

1. INTRODUCTION

The control and reduction of exhaust emissions is the most essential global task [1-3]. To this end, a large number of multidirectional works have been carried out. We can single out several directions of research:

1)   the structural improvement of nodes and systems [4, 5];
2)   the creation of fundamentally new nodes and systems [6, 7];
3)   the development of alternative fuels [8-11];
4)   maintaining the technical condition of vehicles in operation [11-14];
5)   the study of the laws of changes in the technical condition of vehicles and finding the optimal corrective and supporting effects [15, 16].

It is impossible to achieve meaningful progress in the areas indicated in clauses 4) and 5) without internal and external means to control the technical condition of nodes and systems [17]. The lack of control tools which can reliably determine the technical condition of ICE systems leads to high costs during troubleshooting [18, 19]. False malfunctions or missed failures are often recorded [20].

Several articles have noted that in fact, all malfun–ctions associated with degradation of the fuel combus–tion process are reflected in an increase in the content of toxic substances in exhaust gases (Fig. 1) [20, 2].

This leads to subsequent failures of the catalytic converter and oxygen sensors (Fig. 2) [21]. The result is noncompliance with the EURO class, increased toxicity, and significant fines [22].

Let us briefly analyse the diagnostic methods which can be used to determine the technical condition of the

exhaust system (catalytic converter) in particular, directly or indirectly - the content of hydrocarbons in the exhaust gases of the ICE.
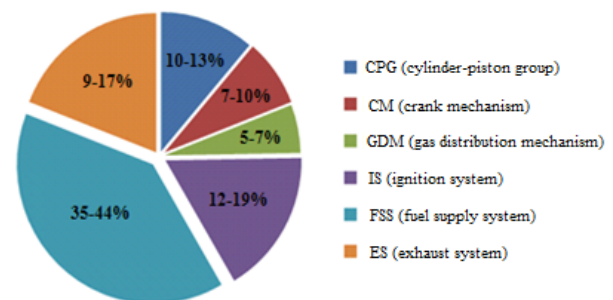

Figure 1. The statistics of car system failures

Figure 2. A catalytic converter with an irreversible change in the internal cells of the catalytic part

There is a known method involving pressure drop before and after the catalytic converter, including the method for pressure pulsations at the outlet [19]. This method is simple to implement, however, its major drawback is the inability to install sensors or mano–meters. Besides, a qualitative analysis of the content of harmful components in exhaust gases is significantly complicated. This is a low-quality method.

In practice, the method of controlling the tempe–rature of individual elements or exhaust gases with the help of a thermal imager or pyrometer is applied. The

temperature of individual elements of the exhaust system partially characterizes the combustion process, but the indirect analysis complicates the search for the epicentre of a failure.

The method of monitoring ICE rundown is also rather well known, but it has major drawbacks related to the influence of many factors on the process of asses–sing the technical condition [17]. This is also a low-quality method.

Today, every car uses an oxygen sensor to control the technical condition of the exhaust system [22]. Ho–wever, when supplying a rich mixture, the sensor itself fails earlier and further control leads to a false diag–nosis.

The methods of direct disassembly and controlling the elements of the exhaust system give little in terms of increasing control reliability [23]. Their use gives too shallow an assessment.

The relevant method applied for years is to control exhaust gases using a gas analyse. This method allows for simultaneous control over a group of parameters in various modes. The drawback is the intake in the common exhaust pipe, which eliminates the selectivity of controlling individual cylinders.

Our analysis of the methods and means used to control exhaust systems showed that a more reliable method is needed [18]. In our case, the appropriate method is to analyse the composition of exhaust gases in individual cylinders (selectively) in test modes [17]. The essence of the method is that the gas is analysed at the points of the exhaust gas exit from each individual cylinder [22]. In this case, the testing effect is provided by a change in the duration of fuel injection, complete and partial interruption of the spark formation and fuel supply in individual cylinders [19].

These aforementioned points have allowed us to formulate the purpose of the research: to increase the reliability of diagnosing ICEs by controlling the con–centration of hydrocarbons in exhaust gases using the selective method of exhaust gas sampling in test modes.

Research objectives:

1. Analyse the statistics of ICE system failures; identify the most vulnerable systems based on an analysis of the advantages and disadvantages of various diagnostic methods; choose the most informative and reliable method.

2. Develop a generalized mathematical model of changes in the composition of exhaust gases depending on changes in the resistance of the catalytic converter, the spark gap of the spark plug, and the capacity of the electromagnetic nozzle.

3. Develop a method for assessing ICE technical condition based on exhaust gas toxicity parameters; design the necessary diagnostic equipment.

4. Experimentally identify the patterns of changes in the composition of exhaust gases depending on changes in the resistance of the catalytic converter, the spark gap of the spark plug, and the capacity of the electro–mag–netic nozzle.

2. THEORETICAL RESEARCH

Changes in the technical condition of the catalytic con–verter is accompanied by an increase in its resistance.

An increase in the resistance of the catalytic converter leads to an exhaust gas delay before it, which subse–quently causes a decrease in the neutralization effici–ency (Fig. 3) [24].
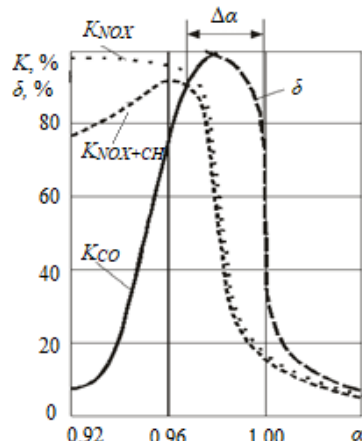
Figure 3. The dependence of the conversion ratio K (%) of the catalytic converter on the excess air ratio, α; δ is the voltage at the working terminals of the λ probe (V); $\Delta\alpha$ is the reference displacement made automatically by the electronic control unit of the ICE; K_{NOX} is the efficiency of processing nitrogen oxides NOX by the catalytic converter (%); K_{NOX+CH} is the efficiency of processing nitrogen oxides NOX and hydrocarbons CH by the catalytic converter (%); K_{CO} is the efficiency of processing carbon oxides CO by the catalytic converter (%)

An increase in the resistance of the converter is accompanied by internal correction of the fuel supply performed by the electronic control unit of the ICE to enrich the mixture. We can see a decrease in the effi–ci–ency of the converter to 10% on the left side of the graph (Fig. 3) in the zone of rich mixtures. Thus, the dynamics of the change in the resistance of the conver–ter is accompanied by over-enrichment of the mixture to the possible efficiency limits with a significant increase in exhaust emissions.

The limiting change in the resistance of the catalytic converter leads to a deceleration of the flow of exhaust gases, which cannot escape in the resulting locked volu–me. The inertia and the amount of exhaust gases inc–rease sharply at significant loads and high speeds of the ICE crankshaft. This results in a blockage and overflow of the gases. The return movement of the exhaust gases into the combustion chamber worsens the cylinder clea–ning and leads to a significant slowdown in the fresh charge supply. As a result, the fuel-air mixture burns poorly with the release of increased toxicity. Thus, at idle and partial loads, the ICE can operate within accep–table limits of changes in the concentration of exhaust gases, and at high loads - with a significant exceedance of statutory limits and complicated combustion.

In the theoretical portion of our research, we analy–sed numerous studies of Russian and foreign authors on monitoring the toxicity parameters of modern vehicles [13, 16]. All the research results were presented as a generalized mathematical model taking into account the composition of exhaust gases before the converter with the technical condition of the catalytic converter, the spark plug, and the electromagnetic nozzle:

$$n = f(Z, F, R) \qquad (1)$$

$$O_2 = f(Z, F, R) \quad (2)$$

$$CH = f(Z, F, R) \quad (3)$$

$$CO = f(Z, F, R) \quad (4)$$

$$CO_2 = f(Z, F, R) \quad (5)$$

where n is the ICE crankshaft speed, rpm; O_2 is the content of oxygen in exhaust gases, %; CH is the content of hydrocarbons, ppm; CO is the content of carbon oxide, %; CO_2 is the content of carbon dioxide in exhaust gases, %; Z is the spark plug gap, mm; F is the capacity of the electromagnetic nozzle, %; and R is the equivalent resistance of the converter, mm.

The data was processed using Matlab Simulink. The calculated model is presented in Fig. 4.
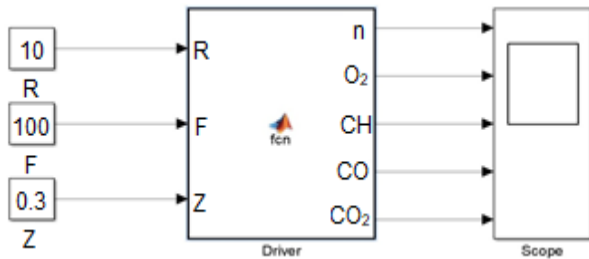

Figure 4. The calculated model in Matlab Simulink

Processing the data in this software provides the dependencies of the technical condition of the ICE elements in the form of graphs of the dependence of CO on the change in the converter resistance R=34–10 mm, the capacity of the nozzle F=94–106%, and the spark gap Z=0.3–1.1 mm.

Let us analyse the dependence of the concentration of CH, ppm in 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 (Figs. 5, 6). Fig. 5 shows the combination of R=10 mm, F=94%, and Z=0.3 mm.
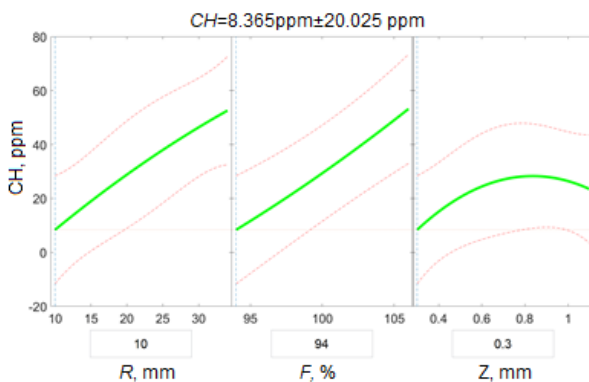

Figure 5. The dependence of the concentration of *CH* in exhaust gases on the equivalent resistance of the catalytic converter *R*=10 mm, the capacity of the electromagnetic nozzle *F*=94 % and the spark plug gap *Z*=0.3 mm

Let us explain how the model works (Figs. 5, 6): the left-hand quadrant shows the change in the resistance of the catalytic converter from the factory nominal to the maximum value according to the ICE operability condition. The centre presents the change in the capacity of the EMN from the minimum possible to the maximum

possible value as limited by the manufacturer. The variation limits of the spark gap of the spark plug are shown on the right.
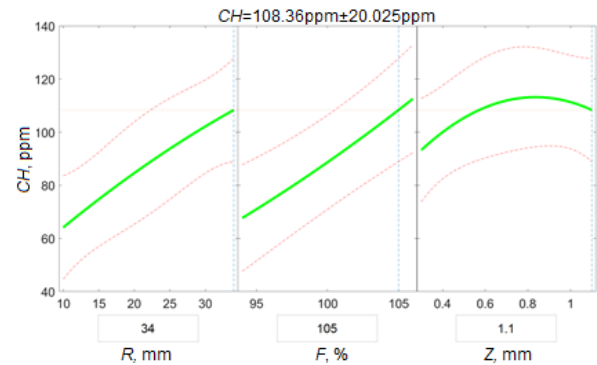

Figure 6. The dependence of the concentration of *CH* in exhaust gases on the equivalent resistance of the catalytic converter *R*=34 mm, the capacity of the electromagnetic nozzle *F*=106 % and the spark plug gap *Z*=1.1 mm.

When the Matlab Simulink application starts automatically, the vertical marker is launched from the point corresponding to 10 mm of resistance of the catalytic converter and, with a certain delay, it moves to the right, passing all possible intermediate resistance values. The model of the second and third quadrants is realized similarly with all possible combinations of the three factors within the given variation limits.

Analysis of the data in Figs. 5, 6 shows that the concentration of CH increases sharply with a decrease in the equivalent resistance at the outlet from 10 to 34 mm. The concentration of CH increases sharply with an increase in the capacity of the electromagnetic nozzles from 94 to 106%. The concentration of CH also increases with an increase in the spark plug gap from 0.3 to 1.1 mm.

3. RESEARCH METHODOLOGY

We designed an experimental setup to carry out the experimental studies and assess the diagnostic parameters (see Fig. 7).
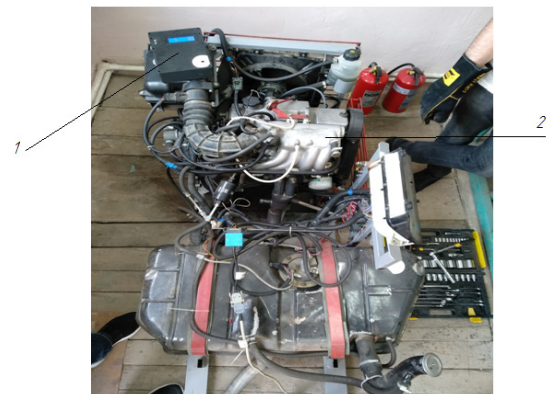

Figure 7. The experimental setup: 1 - loader of the DBD gasoline engine; 2 - power plant based on the VAZ-2114 ICE

It consists of a loader of the DBD-1 gasoline engine (proprietary solution) (1) and a power plant based on the VAZ-2114 ICE (2). We also used a PC with the installed software data package and a MT-10 diagnostic motor tester.

The fuel injection time was set during diagnostics and controlled using the developed DBD-4 device. The information on the current injection time was shown on the device's display (Fig. 8). The injection time can be changed independently for each individual electro–magnetic nozzle.

Figure 8. Fuel injection time control on the display of the DBD-4 device

The ionization voltage of the spark plugs was cont–rolled using a USB-Autoscope III Postolovsky oscillo–scope. The device has high universal applicability for various car brands.

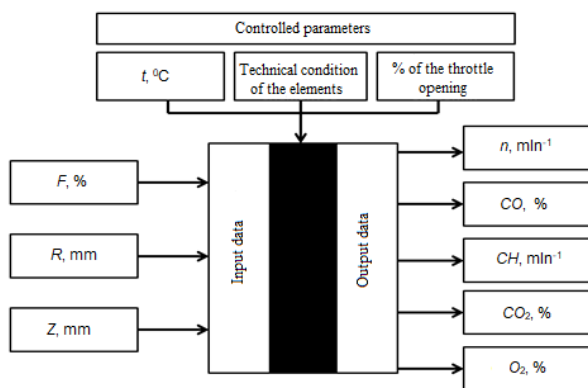We developed a model of input and output factors to carry out the experimental studies (Fig.9).

Figure 9. A model of input and output factors taking into account the controlled parameters

In our studies, the input parameters are the change in the resistance of the catalytic converter, the capacity of the electromagnetic nozzle, and the spark gap of the spark plug. The controlled parameters are the tempera–ture of the ICE coolant, the technical condition of the CPG, the GDM, and the oil temperature. The output parameters are the ICE crankshaft speed, CO, CO_2, CH, and O_2. After that, the data was processed in the Sigma–Plot software suite, verification and comparative studies were carried out in Excel and Mathcad.

Exhaust toxicity was controlled by a 4-component INFRAKAR gas analyser. The gas analyser was prepared for measurements according to the attached guidelines. The gas probe was connected to a probe for individual gas analysis. The parameters obtained during the experiments were recorded in the experimental results registration slips.

To justify the installation site of the gas probe, we developed a 3D model of the exhaust manifold and calculated the exhaust gas flow parameters, based on which we chose the location of the exhaust gas samp–ling point. Using the method of thermometry with highly sensitive thermocouples at the exhaust gas samp–ling points when the VAZ-2114 ICE was idle, our stu–dies measured a temperature of 320-350 ^{0}C depending

on the location of the cylinder. When the ICE operated on four cylinders at n=5,100 rpm, the temperature was 430-460 ^{0}C. When the ICE was loaded by the discon–nection of the three cylinders out of the four working ones (at n=5,100 rpm), the temperature in the exhaust gas intake zone was 650-680 ^{0}C depending on the cylinder removal.

4. THE RESULTS OF THE EXPERIMENTAL STUDIES

Let us consider the relationship between CH content and the capacity of the electromagnetic nozzle and the spark plug gap Z (Fig. 10).
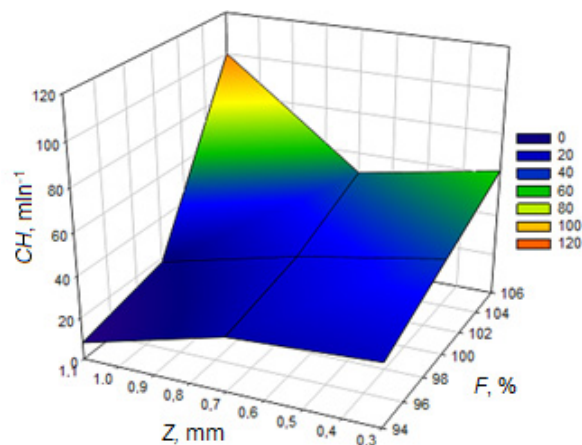

Figure 10. The dependence of the *CH* content on the capa–city of the electromagnetic nozzle *F* and the spark plug gap *Z* (at the resistance of the catalytic converter *R*= 10 mm = *const* and a 20% throttle opening degree)

The dependence in Fig. 10 is approximated by the equation (6):

$$CH(F,Z) = 3346.3280 - 69.9629 \cdot F - 69.1669 \cdot Z + 0.3704 \cdot F^2 + 45.8335 \cdot Z^2 \tag{6}$$

At 94% nozzle capacity with a 1.1 mm spark plug gap, we observed a sharp drop in CH content, ppm. The content in the exhaust gas sample was 8 ppm, which indicates a low fuel content in the fuel-air mixture. With such a small amount of fuel, the ionization voltage is enough for the 1.1. mm spark gap of the spark plug to ignite the fuel-air mixture and achieve complete combustion. At the nominal values of the nozzle capa–city of 100% and the spark plug gap of 0.7 mm, the rea–dings of the CH content were 34 ppm, which indicates that the combustion of the fuel-air mixture is correct. By increasing the nozzle supply to 106% and the spark gap of the spark plug to 1.1 mm, we observe a maximum increase in the CH content in the exhaust gas sample, the amount of which was 100 ppm. This high CH content in the exhaust gas sample directly indicates a malfunction in the fuel system.

Let us consider the relationship between the CH content and the capacity of the electromagnetic nozzle and the resistance of the catalytic converter (Fig. 11).

The dependence in Fig. 11 is approximated by the equation (7):

$$CH(R,F) = 5853.8518 - 8.2963 \cdot R - 122.5185 \cdot F + 0.2593 \cdot R^2 + 0.6481 \cdot F^2 \tag{7}$$
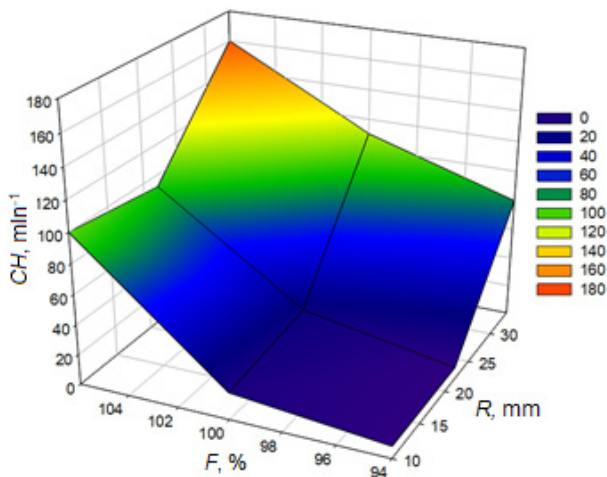
Figure 11. The dependence of *CH* content on the capacity of the electromagnetic nozzle *F* and the resistance of the catalytic converter *R* (at the spark plug gap *Z*=1.1 mm = *const* and a 20% throttle opening degree)

We can see from the presented dependence that at 94% fuel nozzle capacity and 10 mm converter resis–tance, the minimum *CH* content in the exhaust gas sample is 8 ppm, which indicates a poor fuel-air mixture and thus points to a malfunction of the fuel nozzle. With an increase in the capacity of the nozzle and a decrease in the converter resistance, we observed a *CH* content increase in the exhaust gas sample, which indicates incomplete combustion of the fuel-air mixture. At a maximum capacity of the nozzle of 106 % and a nominal resistance of the catalytic converter of 34 mm, we observe the maximum *CH* content in the exhaust gas sample, which indicates a malfunction in the fuel supply system. With this combination of factors, the amount of *CH* in the exhaust gas sample is 160 ppm.

Let us consider the relationship between the *CH* content, ppm, and the spark plug gap and the resistance of the catalytic converter (Fig. 12).
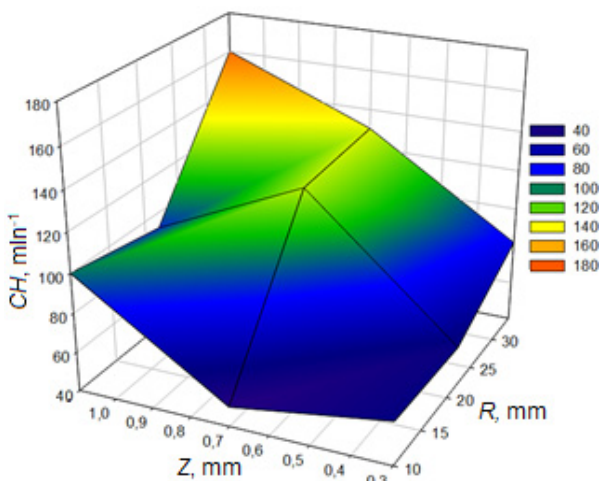

Figure 12. The dependence of the *CH* content on the spark plug gap and the resistance of the catalytic converter (at the capacity of the electromagnetic nozzle *F*= 106% = *const* and a 20% throttle opening degree)

Analysis of the graph shows that the minimum *CH* content, ppm is achieved at the minimum capacity of the catalytic converter of 10 mm and the spark plug gap of 0.7 mm; the *CH* index for this combination of factors is

50 ppm, which indicates that the combustion of the fuel-air mixture is incomplete. With an increase in the spark gap to 1.1 mm and an increase in the capacity of the con–verter to 34 mm, we observe a maximum increase in the *CH* content in the exhaust gas sample, the rate of which is 160 ppm, which indicates that the fuel-air mix–ture is oversaturated and the ionization voltage is insuf–ficient.

The dependence in Fig. 12 is approximated by the equation (8):

$$CH(R, Z) = -6.0648 + 0.7963 \cdot R + 143.3333 \cdot Z + \\ + 0.0324 \cdot R^2 - 58.3333 \cdot Z^2 \tag{8}$$

In the final portion of our experiment, we obtained the dependence of the *CH* concentration in the exhaust gases on the ICE crankshaft speed *n* (Fig. 13).
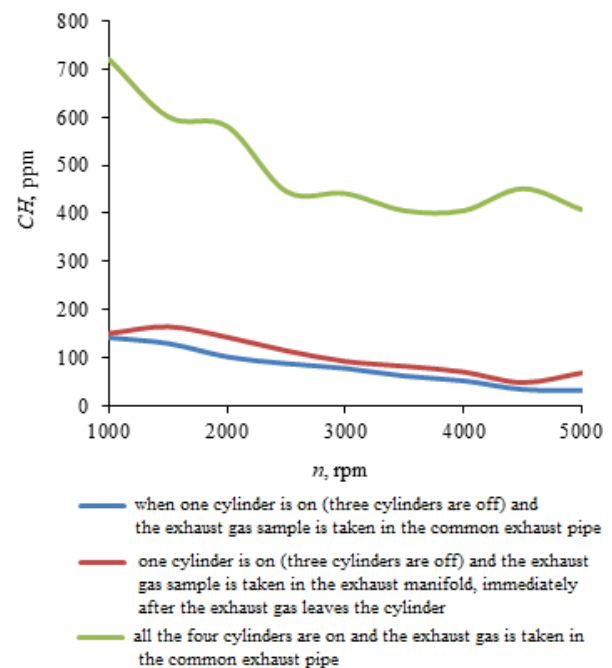

Figure 13. The dependence of the *CH* concentration in the exhaust gases on the ICE crankshaft speed *n*

The performed analysis of the data in Fig. 13 showed that when using the classical method of exhaust gas sampling (when all the four cylinders are on and the exhaust gas sample is taken in the common exhaust pipe), the concentration of *CH* is 3.5-4 times higher than when sampling options 1 and 2 are used. We can say with sufficient accuracy for the experiment that exhaust gas sampling methods 1 and 2 are identical.

5. CONCLUSION

The possibilities of the proposed method are very expansive. This method is used when diagnosing and setting the ICE fuel systems, in particular, when setting the characteristics of an ICE running on gas relative to the option of running on gasoline fuel. Individual moni–toring of the exhaust gases of only one cylinder allows one to evaluate only a single contribution of this cylin–der without the interference of other influences. So, mixing of exhaust gases and the mutual influence of each of the working cylinders on the release process are characteristic to control toxicity in the common exhaust

pipe. The applied method allows one to exclude the mutual influence and to increase the control accuracy and selectivity. In particular, in the future, it provides for the possibility of installing on-board ICE toxicity control devices and a selective assessment of the technical condition of individual ICE elements and systems.

We developed recommendations and a process for assessing the technical condition of the ICE exhaust system based on the analysis of the exhaust gas composition of individual cylinders. Through operati–onal tests, we established that at the combination of the maximum values of the factors (Z=1.1 mm, F=106%, R=34 mm), an unambiguous combination of the output parameters is an increase in CH relative to the nominal value and a decrease in the content of O_2. The com–bination of the minimum values of the factors (Z=0.3 mm, F=94%, R=10 mm) is an unambiguous combi–nation of the output parameters: an increase in CO rela–tive to the nominal value and a decrease in the ICE crankshaft speed. We performed a technical and econo–mic assessment. The average return on investment of the device which allows for the implementation of this method was 3.5 months.

Practical results: we developed a hardware-software complex for test diagnosis of ICE systems and proposed an algorithm for diagnosing ICE through a selective exhaust gas sampling method.

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КОНТРОЛА ЕМИСИЈЕ УГЉОВОДОНИКА ПРИ ПРОМЕНИ ТЕХНИЧКОГ СТАЊА ИЗДУВНОГ СИСТЕМА КОД МОДЕРНИХ АУТОМОБИЛА

В. Шепелев, А. Гритсенко, Г. Салимоненко

Метод који се највише примењује за праћење рада СУС мотора је селективна контрола са поједи–начним корекцијама тренутног техничког стања. Комбинација гасног анализатора, постављеног у сваком колектору, уређаја за испитивање мотора и утоваривача омогућава идентификовање отказа код издувног и свих осталих система са великом пре–цизношћу и предузимање појединачних корекција како би се обезбедили еколошки и економски пара–метри. Развили смо уопштени математички модел промена састава издувних гасова у зависности од промена отпора у каталитичком конвертору, зазора код свећица и капацитета електромагнене млазнице.