Experimental research on operational process of petrol engine on lean air-and-fuel mixtures on the edge of combustion knock

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Abstract. The results of experimental research are provided regarding the operational process of VAZ-21124 petrol engine with the compression ratio of 12.0 on lean air-and-fuel mixtures with various values of heating the air charge at intake, and of the ignition advance angle. In the course of performing the experimental research, the pressure of gases in the engine cylinder was registered, as well as the temperature of the air charge in the intake manifold, the ignition advance angle, and the concentration of toxic components in the exhaust gases. The obtained pressure indicator diagrams were processed using a special program for determining indices of the operating cycle, cycle consumption of fuel and air, air excess factor, and heat release rate. The obtained cycle consumption of fuel and air, as well as the air excess factor were compared to the ones measured experimentally. As a result, possible boundaries of leaning of air-and-fuel mixture were revealed, as well as the values of heating the air charge, and of the ignition advance angle, for intensification of the process of combustion till the knock moment. When the air charge temperature at the intake was raised from 290°C to 112°C, the ignition advance angle retarded from 35.5 to 15 degrees, and the air excess factor decreased from 1.55 to 1.41 respectively.

1. Introduction

The toughening of requirements to ecological performance of reciprocating internal combustion engines leads to searching for the possible ways of reducing the concentration of toxic components in exhaust gases.

One of the ways of improving ecological characteristics of petrol engines is organizing the operational process with the use of lean air-and-fuel mixtures. Though this method may seem simple to fulfill, it has significant disadvantages, which if not solved make it impractical. Those include: increasing the duration of the combustion process, decreasing the efficiency and indicator indices, raising temperature of the exhaust gases, and increasing thermal load on the engine parts.

These disadvantages may be minimized through intensification of the combustion process by heating the fresh charge in the intake manifold at the engine cylinder inlet. Then the temperature of the working medium at the moment of ignition will be high enough for the process of combustion to progress actively. But in this case there is a higher risk of combustion knock, which may be avoided by regulating the ignition advance angle (IAA). As a result it would be possible to organize the
engine’s operation on lean air-and-fuel mixtures on the edge of combustion knock with preservation of the capacity characteristics and improvement of ecological performance.

Heating of fresh charge in an intake manifold is quite often used internationally to control the operational process of a reciprocating internal combustion engine. Thus, in work [1] by Horng-Wen Wu, Tzu-Ting Hsu, Jian-Yi He, Chen-Ming Fan optimal values were selected for the intake air temperature and the recirculation degree of exhaust gases in order to improve the engine’s ecological performance.

In their work [2] Tudor Ulian, Vlad Vornicu, Edward Rakosi, Sorinel Talif developed a mathematical model to assess the effect of heating of the air-and-fuel mixture on the indicators of operation of a spark-ignition engine. The work’s main objective was to determine the charging coefficient, as well as the temperature and pressure of the working medium in the beginning of the process of compression at various crankshaft speeds and values of the intake charge heating.

We also could mention a number of works dedicated to research on the operational process of reciprocating petrol engine on lean air-and-fuel mixtures. For instance, in their work [3] Edward Rakosi, Sorinel Gicu Talif, Gheorghe Manolache performed a many-year studying of operation of a reciprocating petrol engine on lean air-and-fuel mixtures with various values of compression ratio, and the capacity and ecological performance parameters obtained in the process.

The experimental research on the effect of lean mixture on specific fuel consumption, engine capacity, and exhaust gases emissions in a standard petrol engine and the engineered engine with an antechamber was performed by the authors of work [4] Hanlar Bağırov, İbrahim Can, Cengiz Öner, İlker Sugözü, Abdullah Kapıcıoğlu. Where injectors 1, 2 and 3 with nozzles were used for the engineered engine.

Besides leaning of the air-and-fuel mixture, various methods may be used for improving ecological performance of engines. Thus, for instance, the effects of the value of IAA on efficient engine parameters, and NO\textsubscript{X} and CH emissions are studied in the work by Lei Shi, Changwei Ji, Shuofeng Wang, Xiaoyu Cong, Teng Su, Du Wang [5]. This work also describes adding of dimethyl ether to petrol.

In their work [6] Changwei Ji, Jinxin Yang, Xiaolong Liu, Shuofeng Wang, Bo Zhang, Du Wang presented the results of the calculated analysis of the effects of adding hydrogen to an air-and-fuel mixture on the exhaust gases composition. It was determined that adding hydrogen allows to reduce concentrations of CO and CH at some increase in NO\textsubscript{X} content.

Similar results while performing experimental research were obtained by Hayder A. Alrazen, Ahmad K.A. In their article [7] they provide data on the exhaust gases composition of a spark-ignition engine in case a portion of hydrogen is added to the fresh charge.

V.L. Polyacko, V.S. Morozova, V.S. Goun, the authors of work [8], suggested a method of improving ecological performance of a petrol engine by mounting permanent magnets on fuel and air channels. As a result of treating fuel and air with magnetic fluxes of various configurations and intensities, interaction of their molecules in the process of combustion improves, what increases the efficiency of the latter and allows to reduce the content of toxic components in the exhaust gases.

Can Çınar, Fatih Şahin, Özer Can, Ahmet Uyunuz [9] performed comparative research on determining the concentration of toxic components in the exhaust gases of petrol and gas engines with different heights of valves lift. The studies were performed with a fully open throttle plate, and the air excess factor of 1.0, with gradually increasing the height of valves lift. Positive effects were obtained at medium and high crankshaft speeds.

In works [10, 11, 12] a method of improving ecological performance of a petrol engine by means of adding butanol to fuel was suggested and studied. But in this case the efficient capacity and torque somewhat decrease.

The objective of this work was formulated as determining the possible boundaries of leaning air-and-fuel mixture for organizing of low-toxic operational process of a petrol engine with simultaneous regulation of the values of heating fresh charge, and of IAA on the edge of combustion knock.
2. Experimental Research of Reciprocating Engine’s Operational Process

2.1. Method of performing experimental research

Studying of the operational process of a petrol engine on lean air-and-fuel mixtures was performed at the laboratory of the Department of Internal Combustion Engines and Automotive Electronic Systems of South Ural State University (National Research University), on a testing stand with VAZ-21124 engine, and using the equipment by AVL GMBH company ‘figure 1’.

![Figure 1. Testing stand for VAZ-21124 engine.](image-url)

1 – VAZ-21124 petrol engine; 2 – asynchronous electric brake; 3 – torque measuring device; 4 – sensor of the angular position of the crankshaft; 5 – gas analyzer; 6 – catalytic converter of exhaust gases; 7 – valve; 8 – cooler of recirculating exhaust gases; 9 – fuel tank; 10 – fuel injection pump; 11 – ignition module; 12 – fuel filter; 13 – injectors rail; 14 – ignition plug; 15 – gas pressure sensor in the engine cylinder; 16 – intake air heater; 17 – throttle plate; 18 – mixer of recirculating exhaust gases with intake air; 19 – air filter; 20 – AVL air consumption meter; 21 – Bosch sensor of mass air consumption; 22 – IndiCom Light indicator system computer; 23 – indicator system block; 24 – PUMA control system computer; 25 – testing stand control block; 26 – FEMs external module of PUMA control system.

Main engine specifications are given in table 1.

| Engine Type | petrol, 4-stroke, 4-cylinder |
|-------------|-----------------------------|
| Cylinder diameter/ piston stroke, mm | 82 / 75.6 |
| Maximum capacity, kW/min⁻¹ | 65.5 / 5,000 |
| Maximum torque, N*m/min⁻¹ | 131 / 3,700 |
| Compression ratio | 12.0 |

A mode with the following parameters was chosen to perform the testing:
- crankshaft speed of 1,500 min⁻¹;
- degree of throttle plate opening of 35.8%; and
- duration of fuel injection of 9.776 ms.
Meanwhile the air excess factor at normal atmospheric conditions equaled 1.50-1.55 (according to the gas analyzer readings). To raise the intake air temperature from 29°C to 112°C, electric heater was used ‘figure 1’. This lead to decrease of the air excess factor down to 1.37. Regulation of the IAA in the course of the experimental research was performed within the range of 15.0 to 35.5 degrees of crankshaft rotation (deg CR) to the upper dead center.

To increase the compression ratio, the cylinder head was additionally treated. Together with it a special channel was manufactured for installation of a pressure sensor and registration of gas pressure in the engine cylinder. The indicator diagram of the engine operation was registered with high accuracy with a step of one degree of crankshaft rotation. This became possible through using the measuring system by AVL GMBH company, which includes a separate piezoelectric pressure sensor encoder, Indismart 6 Piezo 23, and IndiCom Light software complex 22 ‘figure 1’.

In the course of the testing with the use of PUMA Open software complex 24 ‘figure 1’ by AVL GMBH company, all the main parameters of the engine’s operation were registered (crankshaft speed, capacity, torque, hourly consumption of air and fuel, temperature of fresh charge in the intake manifold, cooling fluid, oils, and others).

To estimate the content of components in the exhaust gases, a 5-component AVTOTEST gas analyzer was used ‘figure 1’. The exhaust gases sampling for the analysis was taken from the exhaust pipe before the converter 6.

The process of combustion of the lean mixture at the absence of fresh charge heating stretched in time. The aftercombustion occurred at the expansion stroke. As a result, the engine performance indicators worsened. Usually this drawback is compensated by increasing the IAA. However, it is reasonable to be increasing it till combustion knock occurs, which is determined either by typical engine “knocking”, or visually by reading the indicator diagram. That is why at the absence of heating in this experimental research the IAA is set for 35.5 degrees of crankshaft rotation, so that combustion on the edge of the knock could be obtained.

In case the fresh charge was heated from 29°C to 112°C, fuel ignition became easier, and the process of combustion intensified. That is why not to allow the combustion knock, the IAA in this experimental research had to be decreased from 35.5 down to 15.0 degrees of crankshaft rotation, that is to make it more delayed.

2.2. Results of the experimental research
In case the fresh charge was heated from 29°C to 112°C, the mass charging of the cylinders with air decreased. The process of fuel combustion in the cylinder also changed. That led to relevant change in pressures in the intake and outtake manifolds. As a result, with the preserved duration of fuel injection, the injection rate somewhat changed. The air excess factor in case of heating decreased respectively.

The main registered parameters are given in tables 2, 3 and 4. Here a method of obtaining a numerical value is indicated for each parameter: ‘meas.’ – using stand equipment; ‘analyz.’ – using AVTOTEST gas analyzer; ‘proc.’ – as a result of the experimental data processing.

### Table 2. Results of VAZ-21124 engine testing (beginning).

| Mode | $t_e$ (°C, meas.) | IAA (deg CR, meas.) | T (N*m, meas.) | Ne (kW, proc.) | $g_t$ (g/(kW*h), meas.) | $N_1$ (kW, proc.) | $p_f$ (MPa, meas.) | $p_i$ (MPa, proc.) | $g_e$ (g/(kW*h), proc.) | $g_e$ (g/(kW*h), proc.) |
|------|----------------|-------------------|--------------|---------------|----------------------|----------------|----------------|----------------|----------------------|----------------------|
| 1    | 29             | 35.5              | 75.5         | 11.86         | 202.8                | 13.14          | 0.701         | 0.658          | 238.6                | 224.6                |
| 2    | 45             | 30.5              | 74.8         | 11.74         | 203.55               | 13.01          | 0.695         | 0.652          | 248.7                | 225.5                |
| 3    | 71             | 23                | 72.7         | 11.43         | 212.18               | 12.39          | 0.674         | 0.62           | 245.8                | 229.9                |
| 4    | 84             | 18.5              | 70.5         | 11.08         | 211.29               | 12.45          | 0.658         | 0.624          | 252.7                | 237.4                |
| 5    | 112            | 15                | 69.5         | 10.91         | 210.62               | 12.50          | 0.646         | 0.626          | 248.4                | 241.4                |

### Table 3. Results of VAZ-21124 engine testing (continued).

| Mode | $t_e$ | $T_a$ | $p_a$ | $T_d$ | $\Delta T$ | $T_{max}$ | $G_{A cyl}$ | $G_{A cyl}$ | $G_{F cyl}$ | $G_{F cyl}$ |
|------|-------|-------|-------|-------|------------|-----------|-------------|-------------|-------------|-------------|

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As a result of the performed experimental research, dependencies of the engine parameters on the indicated power on the torque, efficient capacity and brake specific fuel consumption were built ‘figure 2’. Also here the calculated values of the indicated power are given.

The indicator diagrams of gas pressure in the cylinder at all the studied modes, and graphs of temperatures obtained as a result of their processing are given in ‘figure 3’.

As a result of the performed experimental research, dependencies of the engine parameters on the temperature of the fresh charge at the engine inlet were determined and built for:

- temperature at the beginning of compression $T_{1a}$, value of heating of the fresh charge $\Delta T$, and maximum temperature of gases in the cylinder $T_{\text{max}}$ ‘figure 4’;
- maximum heat release rate $\Delta Q_{\text{max}}$, angle $\phi_{Q_{\text{max}}}$ corresponding to this moment, and IAA ‘figure 5’;
- brake specific fuel consumption $g_{\text{e}}$, and air excess factor $\alpha$ ‘figure 6’;
- cycle consumption of fuel $G_{F_{\text{cycl.}}}$ and air $G_{A_{\text{cycl.}}}$ ‘figure 7’;
- content of hydrocarbon CH and nitrogen oxides $NO_X$ in the exhaust gases ‘figure 8’; and
- content of carbon oxide $CO_2$, carbon dioxide $CO_2$, and oxide $O_2$ in the exhaust gases ‘figure 9’.

Using the measured data of the torque and efficient capacity of the engine, dependencies on the temperature of fresh charge in the intake manifold were built ‘figure 2’. Also here the calculated values of the indicated power are given.

**Figure 2.** Dependencies of the torque, efficient capacity and indicated power on the temperature of fresh charge in the intake manifold.

| Mode | $t_{k}$ (°C, meas.) | $\Delta Q_{\text{max}}$ (J/deg proc.) | $\phi_{Q_{\text{max}}}$ (deg CR proc.) | $\alpha$ (meas.) | $\alpha$ (analyz.) | CO (% analyz.) | CH (ppm, analyz.) | NO$_X$ (ppm, analyz.) | CO$_2$ (%) analyz. | O$_2$ (%) analyz. |
|------|---------------------|---------------------------------------|---------------------------------------|------------------|------------------|---------------|-----------------|-------------------|-----------------|------------------|
| 1    | 29                  | 26.04                                 | 16                                    | 1.454            | 1.544            | 0.1           | 224             | 2,181             | 9.22            | 7.57             |
| 2    | 45                  | 21.23                                 | 18                                    | 1.386            | 1.525            | 0.1           | 218             | 2,585             | 9.31            | 7.38             |
| 3    | 71                  | 15.87                                 | 21                                    | 1.399            | 1.479            | 0.1           | 201             | 2,368             | 9.69            | 6.99             |
| 4    | 84                  | 16.69                                 | 18                                    | 1.378            | 1.451            | 0.1           | 173             | 2,381             | 9.86            | 6.67             |
| 5    | 112                 | 24.28                                 | 22                                    | 1.374            | 1.413            | 0.09          | 150             | 3,169             | 9.9             | 6.11             |

**Table 4. Results of VAZ-21124 engine testing (ending).**
Figure 3. Indicator diagrams of gas pressure in the cylinder and graphs of temperatures at the studies modes.

Figure 4. Dependencies of temperature at the beginning of compression $T_s$, value of heating of the fresh charge in the cylinder $\Delta T$, maximum temperature of gases $T_{\text{max}}$ on the temperature of fresh charge.

Figure 5. Dependencies of maximum heat release rate $\Delta Q_{\text{max}}$, angle $\varphi_{Q_{\text{max}}}$ corresponding to this moment, and ignition advance angle on the temperature of fresh charge.
3. Analysis of the Experimental Research Results

The obtained data reveal that increase in the temperature of fresh charge at the intake is accompanied by decrease in the air excess factor ‘figure 6’. This happens as a result of decrease in the density of the air charge and cycle consumption of air ‘figure 7’.

At the increase of temperature of the fresh charge at the intake, the IAA was decreased ‘figure 5’. It was regulated according to the moment of consumption knock occurring in the engine cylinder.

The linearity of decreasing of the IAA is disturbed at the modes with temperature of 71 and 84°C, when excessive values of mass air consumption ‘figure 7’ and of the air excess factor ‘figure 6’ are observed. This is also the reason for low values of the maximum heat release rate ‘figure 5’, and maximum temperature of gases in the cylinder ‘figure 4’ at these modes.

Figure 6. Dependencies of brake specific fuel consumption $g_e$, and air excess factor $\alpha$ on the temperature of fresh charge.

Figure 7. Dependencies of cycle consumption of fuel $G_{F\,cyl}$ and air $G_{A\,cyl}$ on the temperature of fresh charge.

Figure 8. Dependencies of content of hydrocarbon CH and nitrogen oxides NO\textsubscript{X} in the exhaust gases on the temperature of fresh charge.

Figure 9. Dependencies of content of carbon oxide CO, carbon dioxide CO\textsubscript{2}, and oxide O\textsubscript{2} in the exhaust gases on the temperature of fresh charge.
It was determined that with the increase in the intake air temperature, the numerical values of the brake specific fuel consumption grow (figure 6), and cycle consumption of fuel somewhat decreases (figure 7). It is worth noting that the numerical values of these parameters obtained by direct measuring and while processing the indicator diagrams differ by 2.5-9.5%.

Judging by the results of measuring concentrations of the components of the exhaust gases sampled at the intake manifold and before the catalytic converter of the exhaust gases, the following may be noted. With the increase in the temperature of the intake charge and the decrease of the air excess factor, the concentrations of NO\(_X\) and CO\(_2\) expectedly increase (figure 8), and the concentrations of CH, CO, and O\(_2\) decrease (figure 9). The general tendency of decrease in CH and growth of NO\(_X\) in this case is somewhat disturbed at the modes with temperature of 71 and 84°C due to excessive (for these modes) values of mass air consumption and of the air excess factor. Despite the general dynamics of growth in NO\(_X\) concentration, it still turns out to be significantly lower than the statistically average values for this type of engine at the studied mode (5,000-5,500 ppm). Low concentration of toxic components in the exhaust gases of this engine allows to considerably alleviate the work of the catalytic converter of the exhaust gases (figure 1).

4. Conclusion

The following conclusions may be drawn from the results of the performed research:

- the operation cycle was studied for the reciprocating petrol engine with the compression ratio of 12, and heating of the air charge at the intake to 112°C during operation on a lean mixture with the air excess factor of up to 1.55 on the edge of the consumption knock;
- as a result of processing the indicator diagrams at the studied modes, the numerical values of the maximum temperatures (2,060-2,350 K) and heat release rates in the petrol engine cylinder (16-26 J/deg CR) were determined;
- a possibility of intensification of the process of combustion was demonstrated by means of heating the fresh charge at the intake to 112°C, and regulating the IAA (from 35.5 to 15 degrees) on the edge of the knock accordingly;
- the obtained changes in the parameters of the engine and the operating cycle depending on the temperature of the fresh charge in the intake manifold agree with the generally known patterns; and
- the results obtained by direct measurement and processing of the indicator diagrams have the maximum differences only in the cycle fuel consumption (2.5-9.5%).

5. References

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