Load characteristics of a turbocharged diesel engine when working on natural gas

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Abstract. The article presents the load characteristics of the diesel D-245.7 when working on the gas-diesel process. The graphs of changes in the parameters of the combustion process, heat release characteristics, and effective indicators are given. It is important to study the issues of converting diesel engines to natural gas, as diesel engine is the most common in the national economy. The most suitable way of converting diesel engines to natural gas is to implement a gas-diesel workflow, since it does not require a significant engine rework. Diesel D-245.7 was chosen as an object of study. In the course of the study, among other things, the load characteristics of this diesel engine were removed when working on the gas-diesel process. When analyzing the experimental data obtained for a gas-diesel process as compared to a diesel one, some features can be noted. The gas-diesel process shows an increase in the temperature and pressure of gases in the cylinder. Heat dissipation is much faster. This indicates the volumetric nature of the ignition and combustion of natural gas. Engine power during the transition to the gas-diesel process is maintained at the same level, while the consumption of diesel fuel due to replacement by natural gas is reduced several times.

1. Introduction
Currently, a rise in the cost of diesel fuel and petrol as well as the scarcity of fuel reserves make the efforts on converting motor transport to alternative fuels a highly desirable proposition. Natural gas is among the list of alternative fuels. At present the cost of natural gas at filling stations is less than 50% of petrol or diesel fuel cost. Though the natural gas consumption is the same.

In the national economy cargo and passenger transport equipped with diesel engines as the power plant is most commonly used. Converting diesel engines to natural gas is easier to be done according to the gas-diesel process. The advantage of this method of conversion lies in the ability to use it for diesel engines which are in service now by modernizing them a little without changing the design significantly [1].

Diesel engine structure is being permanently improved, thrust augmentation ratio increases, specific power output rises. Engines equipped with charging and after cooling systems are increasingly used in motor transport. The problem of converting such engines to natural gas has been partly studied already [2]. However, the transition of high performance diesel engines of low dimension to natural gas is still understudied.
2. Methods
In the research laboratory of the Vyatka State Agricultural Academy the studies on converting car diesel engines to natural gas were carried out within the research theme «Improving operation factors of diesel engines by using alternative fuels».

Diesel D-245.7 was taken as the object for the research. This engine had charging and after cooling systems. Gas-diesel process with this engine was carried out as follows: natural gas was forced into the intake manifold through mixing and metering unit fitted additionally, ignition diesel oil was admitted by standard fuel injector nozzles. Load mode of the engine varied according to the amount of natural gas charge, the cycle quantity of the injected ignition diesel oil remained unchanged in all operation modes. The experimental setup (figure 1) was provided with instruments and equipment for measuring power, economical, and ecological parameters of the engine. Indicator diagrams of the work process were taken by the MAI-5A unit. Load moment on the crankshaft was produced by the electro-brake testing bench SAK-N670.

3. Results
Recording load characteristics was one of the research stages. At this stage there were determined the parameters of the combustion process, heat release characteristics, and effective indicators.

3.1. Combustion process parameters
In figure 2 there are combined graphic charts of the combustion process parameters by the nominal speed (n=2400 min⁻¹) in dependence to the load variation for two work processes. The first is a diesel process, that is, running only on diesel fuel. The second one is a gas-diesel process, that is, running on natural gas introducing an ignition charge of diesel oil. The combustion process parameters were determined when processing the indicator diagrams.

The graphic charts show: maximum mean gas temperature in the cylinder Tₘₐₓ; peak firing pressure pₕₘₐₓ; pressure ratio λ; maximum rate of gas pressure (dp/dφ)ₘₐₓ; ignition delay period φᵢ; mean effective pressure pₑ.
When studying the parameters of the gas-diesel process, the following should be mentioned. The values of maximum gas temperature $T_{\text{max}}$ of the gas-diesel process lie higher than those of the diesel one. Thus, at light load ($p_e = 0.126$ MPa) the $T_{\text{max}}$ value is 1680 K (28% increase), at nominal load ($p_e = 0.947$ MPa) the $T_{\text{max}}$ value is 2350 K (16% increase). The peak firing pressure $p_{z_{\text{max}}}$ at $p_e = 0.126$ MPa is 8.9 MPa (9% lower than in the diesel process), and at $p_e = 0.947$ MPa it is 14.6 MPa (6% rise). The value of pressure ratio $\lambda$ within the interval of loads from $p_e = 0.126$ MPa to $p_e = 0.947$ MPa in the gas-diesel process varies from 1.55 to 1.85, respectively. The $(dp/d\varphi)_{\text{max}}$ value varies from 0.44 to 0.93 MPa/degree of crankshaft rotation. The ignition delay period $\varphi_i$ varies from 10.8 to 9.5 degree of crankshaft rotation.

The reason for the difference between the graphics of gas-diesel and diesel processes is in volumetric mechanism of ignition and burning natural gas. A significant increase in the parameters is observed mainly by heavy load mode, when the ratio of natural gas in the total amount of fuel admitted into the cylinder becomes considerable [3].

It also should be noted that the achieved $T_{\text{max}}$ and $p_{z_{\text{max}}}$ values are below maximum allowed values for internal combustion engines. It means that rise in temperature and pressure in the cylinder should not affect the engine service life. The value $(dp/d\varphi)_{\text{max}}$ of the gas-diesel process does not exceed the maximum allowed value of 1.0 MPa/degree specified by the producing plant.

3.2. Heat release characteristics

In figure 2 there are heat release parameters of diesel and gas-diesel processes. These characteristics were calculated on the basis of obtained indicator diagrams and combustion process parameters.

The graphic charts show: crankshaft rotation angle relative to the top dead center, at the moment of maximum temperature in the cylinder $\varphi_{T_{\text{max}}}$; active heat release, at the time of peak firing pressure in the cylinder $\chi_{p_{z_{\text{max}}}}$; active heat release, at the time of maximum temperature $\chi_{T_{\text{max}}}$; maximum rate of relative heat release $(d\chi/d\varphi)_{\text{max}}$.

As it is shown, the graphs of the gas-diesel process differ from those of the diesel one. Within the interval of loads from $p_e = 0.126$ MPa to $p_e = 0.947$ MPa the angle $\varphi_{T_{\text{max}}}$ in the gas-diesel process varies from 12.5 to 10.5 degree of crankshaft rotation, respectively. The value $\chi_{p_{z_{\text{max}}}}$ varies from 0.38 to 0.71 relative unit. The value $\chi_{T_{\text{max}}}$ varies from 0.45 to 0.8 relative unit. The value $(d\chi/d\varphi)_{\text{max}}$ varies from 0.177 to 0.155 relative unit per a degree of crankshaft rotation.
Along with the load growth there is an increase in $\chi_{iP_{z\max}}$ and $\chi_{iT_{\max}}$ values, specific both for diesel and gas-diesel processes. It can be explained by firing augmentation, taking place due to the rise in temperature and pressure during the intake in turbocharged engines. The values of heat release parameters in the gas-diesel process are higher than the parameters in the diesel one due to the transition to volumetric mechanism of igniting and burning. In the gas-diesel process the most part of fuel is consumed at the initial phases of combustion in the cylinder [4].

3.3 Effective indicators

In figure 3 there are effective indicators of diesel and gas-diesel processes.

The graphic charts show: engine brake horsepower $N_e$; hourly and specific consumption of diesel oil in diesel process $G_f$ and $g_e$, respectively; hourly and specific total consumption of diesel fuel and natural gas in gas-diesel process $G_{f\Sigma}$ and $g_{e\Sigma}$, respectively; hourly consumption of ignition diesel fuel in gas-diesel process $G_{fign}$; effective efficiency $\eta_e$; hourly air consumption $G_a$; charge ratio $\eta_v$; excess air coefficient $\alpha$; exhaust gas temperature $t_g$; charging pressure $P_K$; temperature in the intake manifold at the turbocharge output $t_{ch}$ and at the after cooler output $t_{cool}$.

When studying the graphs, it can be said that the effective indicators of the gas-diesel process fully comply with the diesel one. For both processes the brake horsepower $N_e$ rises respectively with load increase from 12 kW at $p_e = 0.126$ MPa to 90 kW at $p_e = 0.947$ MPa.

Within the interval of loads from $p_e = 0.126$ MPa to $p_e = 0.947$ MPa the hourly total consumption of diesel oil and natural gas $G_{f\Sigma}$ during the gas-diesel process varies from 9.6 kg/h to 18.8 kg/h, respectively. Consumption of ignition diesel fuel $G_{fign}$ during the gas-diesel process remains constant throughout the load range and it is 3.6 kg/h. Thus, it can be established that by transition from diesel to gas-diesel process the saving of diesel fuel will reach from 47 to 83% (due to substitution of it for natural gas). Specific total consumption of diesel fuel $g_{e\Sigma}$ at $p_e = 0.3$ MPa is 430 g/kWh, at $p_e = 0.947$ MPa it is 208 g/kWh.

![Figure 3. Effective indicators of D-245.7 diesel at $n = 2400$ min$^{-1}$: --- - diesel process, --- - gas-diesel process.](image-url)
As it is shown in the graphs, fuel consumption during the gas-diesel process by light and average load is higher than during the diesel one and lower by nominal load. Lower fuel consumption by nominal load is due to the fact that natural gas has larger heating effect of mass unit than diesel fuel [5]. But in general, the use of heating effect of fuel during the gas-diesel process in the engine with standard parameters of combustion chamber is less efficient. As it is shown, the graph of effective efficiency $\eta_e$ of the gas-diesel process lies lower than that of the diesel one. Values of efficiency of the gas-diesel process are from 0.102 to 0.363.

During the gas-diesel process within the interval of load change from $p_e = 0.126$ MPa to $p_e = 0.947$ MPa an hourly air consumption $G_a$ varies from 455 kg/h to 533 kg/h. As compared to the diesel process an hourly air consumption decreases due to substitution of an air portion in the intake manifold for natural gas. On the other hand, the decrease in air consumption leads to drop in charge ratio $\eta_v$ and excess air coefficient $\alpha$.

During the gas-diesel process throughout the load range the $\eta_v$ value is about 0.91 [6]. By transition to gas-diesel process exhaust gas temperature $t_g$ decreases (after the turbocharger). It ranges from 181ºC (at $p_e = 0.126$ MPa) to 367 ºC (at $p_e = 0.947$ MPa). Pressure and temperature at the points of the intake manifold by transition from diesel to gas-diesel process change little, if at all. Charging pressure $P_K$ is from 0.138 MPa to 0.172 MPa. Temperature in the intake manifold at the turbocharge output $t_{ch}$ is from 81ºС to 119ºС. Temperature at the after cooler output $t_{cool}$ is from 47ºС to 68ºС [7]. The results of bench tests are summarized in table 1.

| The indicator                                      | Operating mode |
|----------------------------------------------------|----------------|
|                                                   | $p_e=0.126$ MPa | $p_e=0.947$ MPa | $p_e=0.126$ MPa | $p_e=0.947$ MPa |
| Maximum gas temperature in the cylinder, K         | 1310           | 2020           | 1680           | 2350           |
| Maximum pressure in the cylinder, MPa              | 9.8            | 13.8           | 8.9            | 14.6           |
| Pressure ratio                                     | 1.58           | 1.60           | 1.55           | 1.85           |
| Maximum rate of gas pressure, MPA/degree           | 0.55           | 0.78           | 0.44           | 0.93           |
| Ignition delay period, degree of crankshaft rotation | 11.2          | 9.0            | 10.8           | 9.5            |
| Engine brake horsepower, kW                        | 12             | 90             | 12             | 90             |
| Hourly fuel consumption, kg/h                      | 6.8            | 21.0           | 9.6            | 18.8           |
| Efficiency                                         | 0.162          | 0.380          | 0.102          | 0.363          |
| Hourly air consumption, kg/h                       | 455            | 591            | 455            | 533            |
| Excess air coefficient                             | 4.86           | 2.0            | 3.03           | 1.69           |
| Exhaust gas temperature, ºC                        | 197            | 430            | 181            | 367            |

4. Conclusion

On basis of the material submitted, the following conclusions should be made:

- transition of regular diesel engine to working on the gas-diesel process does not require significant rework in its design; it mainly includes fitting of gas mixing and metering unit into the intake manifold and resetting a standard high-pressure fuel pump [8];
- when diesel engine runs on the gas-diesel process, the pressure and temperature in the cylinder increase as compared to the diesel process, though the values of indicators do not exceed the
maximum allowed values specified by the producing plant, i.e. it can be established that engine service life remains unchanged [9]:

- engine power during the gas-diesel process fully complies with the diesel one;
- when diesel runs on the gas-diesel process, significant decrease in diesel oil consumption is achieved due to substitution for natural gas, effective efficiency reduces slightly.

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