Investigation of the speed regime of tractor diesel engine running on natural gas with recirculation

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Abstract. The work is devoted to the use of compressed natural gas as an alternative motor fuel to reduce the toxicity of exhaust gases of tractor diesel engines. At the same time, the urgency of using natural gas in combination with exhaust gas recirculation (EGR) (EGR was used to reliably reduce nitrogen oxides increased as a result of the use of natural gas) in diesel was substantiated. The paper presents the results of experimental studies on the effect of natural gas and EGR on the effective characteristics, combustion process indicators, the toxicity and smokiness of exhaust gases depending on the change in the speed of the crankshaft of the tractor diesel. On the basis of the results of the study, it is proposed to maintain the following ratio: natural gas – 80%, the fuse portion of diesel fuel – 20%. When working on natural gas with EGR, the regularity of supply of recirculated gases from 20 to 40% depending on the mode of operation of the tractor diesel is established. The paper defines and presents the optimal values of the effective parameters, characteristics of the combustion process, toxicity and smoke exhaust gases when working tractor diesel 4F 11.0/12.5 on natural gas with EGR. The translation of the specified diesel fuel oil to natural gas helped to reduce the contents in the exhaust gases when working with EGR 20% of the exhaust gas of nitrogen oxides by 43.2%, of carbon black in a 5.6 times that of carbon dioxide 33.3%, carbon monoxide by 10.0%.

1. Introduction
The steady increase in the consumption of mobile oil fuel and the constant tightening of environmental requirements for it compels mankind to seek alternative energy sources, since their use should reduce the environmental damage caused to the environment, as a result of the use of oil fuels [1–4].

Reduction of the share of transport in pollution is one of the main state priorities defined by the Transport strategy of the Russian Federation till 2030 approved by the order of the Government of the Russian Federation No 1734-р of 22.11.2008. In order to reduce the negative impact of transport on the environment, it is planned to develop and implement mechanisms of state regulation that motivate the transfer of vehicles to environmentally friendly fuels. Currently, among all modes of transport, the problem of increasing the environmental purity of exhaust gases is most acute for mobile agricultural machinery. The increasing relevance of this problem for tractors and other agricultural machinery equipped with diesel engines is due to the existing and planned introduction of emission control standards for toxic exhaust components [5–9].

In the exhaust gases of a tractor diesel engines running on fuel oil that contains more than 200 toxic components. One of the most harmful are nitrogen oxides and solid particles consisting mainly of soot. Of all the variety of existing methods to reduce the toxicity of exhaust gases, the greatest effect can be achieved by the use of alternative fuels that are less prone to soot formation in the combustion
chamber due to the characteristics of the chemical composition and at least physical properties. First of all, natural gas can be attributed to such fuels [10–14].

2. Experimental
In Vyatka state agricultural Academy on the basis of the Department of thermal engines, Vehicles and tractors experimental researches of tractor diesel 4F 11.0/12.5 for work on natural gas with EGR were carried out [15].

In order to determine and optimize the basic parameters of the diesel when working on compressed natural gas with EGR, its bench studies on diesel, gas-diesel and gas-diesel processes with EGR were carried out. It was found that diesel is stable on compressed natural gas at a ratio to nominal conditions: gas – 80%, the ignition portion of diesel fuel – 20%. Further study of the process was carried out in this ratio.

The experimental setup consisted of the SAK-N670 electrothermal stand with the balancing pendulum mechanism (Figure 1), the tractor diesel 4F 11.0/12.5 equipped with the exhaust gas recirculation system (Figure 2), the measuring equipment.

![Figure 1. Electroforming stand, where a is stand; b is balance pendulum machine.](image1)

![Figure 2. General view of the engine mounted on the stand, where a is view of the EGR system; b is view of the mixer-dispenser of natural gas and recycled gas supply.](image2)

3. Results and Considerations
According to power and economic performance of a tractor diesel engine 4F 11.0/12.5, depending on the change of the rotation frequency without regulatory branches is presented in Figure 3.

Analyzing the curves corresponding to the operation of the diesel on natural gas, it can be noted that the increase in the rotational speed leads to an increase in the hourly fuel consumption of \( G_f \), the fuse portion of the diesel fuel \( G_{DF} \), the effective power of \( N_e \), the hourly air consumption of \( G_a \) and the temperature of the exhaust gases \( t_r \). The value of the specific effective fuel consumption is \( g_e \) minimal at a speed of 1700 min\(^{-1}\) and is 198 g/(kW·h). The value of the effective coefficient of efficiency \( \eta_e \) maximum at a rotational speed of 1700 min\(^{-1}\) and is 0.37. Torque \( M_t \) maximum at speed of 1700 min\(^{-1}\)
and is 259 N·m. The Coefficient of excess air \( \alpha \) with increasing frequency of rotation decreases slightly. Analyzing the operation schedules of the natural gas diesel with EGR, it is clear that when the gas diesel with EGR 10% operates, the effective power and torque remain practically at the level of the gas-diesel process without EGR. By increasing the degree of EGR up to 20% there is a decrease in effective power and torque. Thus, the use of EGR 20% at \( n=1400 \text{ min}^{-1} \) results in a 2.5% drop in the effective power of the gas-diesel process without EGR. When working on gas-diesel process by increasing the frequency of rotation in the range from 1400 to 2400 \( \text{min}^{-1} \), \( g_e \) varies from 204 to 213 \( g/(\text{kW} \cdot \text{h}) \), when operating on natural gas with 10 and 20% EGR it varies from 207 to 218 \( g/(\text{kW} \cdot \text{h}) \) and from 214 to 224 \( g/(\text{kW} \cdot \text{h}) \), respectively.

Thus, the application of 10 and 20% EGR in the range \( n \) from 1400 to 2400 \( \text{min}^{-1} \) results in an increase of \( g_e \) to 1.5±2.4% and up to 4.9±5.2%, respectively. The effective efficiency factor, the maximum of which is achieved at a frequency that corresponds to the maximum torque, for the gas-diesel process is 0.37, and for gas – diesel with EGR 10 and 20% - 0.36 and 0.35, which is lower by 2.7 and 5.4% respectively. During the operation of the gas diesel with exhaust gas recirculation, the hourly air flow rate and the ratio of the increase in the EGR degree decrease. The exhaust gas temperature when operating with the recirculation decreases slightly with increasing degree of recycling. The temperature of the EGR gases at work with EGR 20% at all speed modes does not exceed 67°C.

The content of toxic components in the exhaust gases of the tractor diesel 4F 11.0/12.5 depending on the change in the rotational speed is shown in Figure 4.

Analyzing charts of the content of toxic components when working on gas-diesel and gas-diesel processes with EGR, it can be noted that the nature of the curves corresponds to the diesel process, while only their numerical values change. Thus, when working on a gas-diesel process with a EGR 20% with an increase in the rotational speed from 1400 to 2400 \( \text{min}^{-1} \), the content of nitrogen oxides (\( \text{NO}_x \)) decreases from 900 to 700 ppm, or by 22.2%, which is lower than the diesel process by 30.8 and 30.0% respectively. The content of total hydrocarbons increases both with increasing rotational speed and with the use of natural gas. Thus, the use of natural gas in the range of rotational frequencies from 1400 to 2400 \( \text{min}^{-1} \) leads to an increase in the total hydrocarbon content (\( \text{CH}_x \)) in the exhaust gases by 6.8 and 4.0 times respectively.
Figure 4. The impact of the use of natural gas and the EGR on the content of toxic components in the exhaust gases of a tractor diesel engine 4F 11.0/12.5 based on of changes in the frequency of the crankshaft at $\Theta_{\text{inj}} = 23^\circ$, where --- is diesel fuel; --- is gas-diesel fuel; --- is gas-diesel fuel with EGR 10%; --- is gas-diesel fuel with EGR 20%.

The use of EGR 10% in the gas diesel results in a decrease of 11.8% and 9.1%, respectively. But the use of EGR 20% on the gas diesel causes an increase in the $\text{C}_n\text{H}_m$ content in the exhaust gases by 8.8 and 15.9% for the rotation frequencies of 1400 to 2400 min$^{-1}$, respectively. Increasing the rotational speed causes an increase in the carbon monoxide (CO) and carbon dioxide (CO$_2$) content of the exhaust gases. The use of natural gas causes a decrease in the content of oxide and carbon dioxide, and with an increase in the EGR, the content of CO and CO$_2$ increases again.

But still, when the gas diesel with EGR 10% in the range of rotation frequencies from 1400 to 2400 min$^{-1}$ decreases by 2.4 times and by 20.8% respectively, and a decrease in CO$_2$ by 46.0 and 43.6% in relation to the diesel process. Analyzing the content of soot (C) in the exhaust gases, we see that with an increase in the rotational speed, the soot content in the exhaust gases is increased both in the gas-diesel and in the gas-diesel processes with the EGR. The use of natural gas significantly reduces the soot content of the exhaust gases, and the use of EGR leads to an increase in the soot content, and with an increase in the EGR, the soot content increases. Thus, when the gas diesel operates in the range of rotation frequencies from 1400 to 2400 min$^{-1}$, the particulate content decreases by 8.8 and 5.1 times, respectively, in relation to the diesel process. The use of the same EGR 10% causes an increase in particulate matter, which does not exceed 10%.

Figure 5 shows the combustion process parameters of the tractor diesel 4F 11.0/12.5 depending on the change in speed.

Considering the operation of the diesel engine on natural gas, it is clearly seen that with an increase in the rotational speed there is a decrease in the maximum averaged temperature of the gases in the cylinder ($T_{\text{max}}$), maximum pressure ($p_z$), the degree of pressure increase ($\lambda$), the rigidity of the combustion process ($\frac{dp}{d\phi}$)$_{\text{max}}$ and an increase in the angle corresponding to the ignition delay period ($\phi_{\text{i}}$). Thus, in the speed range from 1200 to 2400 min$^{-1}$, $T_{\text{max}}$ decreases from 3100 to 3000 K, or by 3.2%; $p_z$ max from 10.9 to 8.1 MPa, or by 25.7%; $\lambda$ from 2.56 to 1.94, or by 24.2%; ($\frac{dp}{d\phi}$)$_{\text{max}}$ 0.98 to 0.61 MPa/deg, or 37.8%, and an increase of $\phi_{\text{i}}$ from 19.0° to 33.5° of crankshaft rotation, or 14.5° of crankshaft rotation. In the case of natural gas diesel with EGR, the nature of the curves coincides with the gas-diesel process completely, and the values of the graphs "lie" below the curves of the gas-diesel process (except $\phi_{\text{i}}$) throughout the speed range and decrease with an increase in the EGR. Thus, when working on a gas-diesel process with a EGR 10% in the range from 1200 to 2400 min$^{-1}$, there is a decrease in the maximum averaged temperature by 200 K in comparison with the gas-diesel process, the maximum pressure by 7.3–4.9%, the degree of increase in the pressure $\lambda$ by 6.3–5.3%, the rigidity...
of the combustion process by 18.4–8.2% and an increase in the angle \( \phi_i \) from 0 to 0.5°. The application of the same EGR 20% in the range from 1200 to 2400 min\(^{-1}\) leads to a decrease in relation to the gas-diesel process of the maximum averaged temperature by 350–400 K, the maximum pressure by 11.0–13.6%, the degree of increase in the pressure \( \lambda \) by 10.2–12.4%, the rigidity of the combustion process by 33.7–11.5% and an increase in the angle from 0.5 to 2.5°.

**Figure 5.** The impact of the use of natural gas and EGR on the performance of the combustion process of a diesel engine 4F 11.0/12.5 based on changes in the frequency of the crankshaft at \( \Theta_{\text{ij}} = 23° \), where — is diesel fuel; — is gas-diesel fuel; — is gas-diesel fuel with EGR 10%; — is gas-diesel fuel with EGR 20%.

The use of EGR at the gas diesel 4F 11.0/12.5 makes it possible to effectively reduce the toxicity of exhaust gases by nitrogen oxides. The main issue to be solved when equipping the gas diesel with an EGR system is the development of an automatically controlled drive that changes the law of control of the exhaust gas bypass depending on the mode of operation of the gas diesel. The dependence of the change in the EGR from the load of the tractor diesel 4F 11.0/12.5 when operating on natural gas is shown in Figure 6.

**Figure 6.** The dependence of the degree of EGR gas diesel 4F 11.0/12.5 from load.

For all frequencies of rotation of a cranked shaft of the tractor diesel engine increasing the EGR for different load modes leads to a larger decrease in the concentration of nitrogen oxides in the exhaust gases.

**4. Conclusion**

1. On the basis of the results of researches of tractor diesel 4F 11.0/12.5 it is offered to support the following ratio: natural gas - 80%, the fuse portion of diesel fuel - 20%.
1. When working on natural gas with EGR, the regularity of supply of recirculated gases from 20 to 40% depending on the mode of operation of the tractor diesel is established.

2. The possibility of maintaining the power parameters of the tractor diesel 4H 11.0 / 12.5 when operating on natural gas with EGR at the level of serial diesel: $N_c = 55.2$ kW ($n=2200\ \text{min}^{-1}$), $N_c = 46.5$ kW ($n=1700\ \text{min}^{-1}$).

3. The values of combustion process parameters are determined. The nominal speed mode: diesel process - $T_{\text{max}} = 2190\ \text{K}$; $p_c = 8.1\ \text{MPa}$; $\lambda = 1.90$; $(dp/d\phi)_{\text{max}} = 0.059\ \text{MPa/deg}$; $\varphi = 22.5^\circ$; gas-process - $T_{\text{max}} = 3010\ \text{K}$ (increase by 37.4%); $p_c = 8.5\ \text{MPa}$ (increase by 4.9%); $\lambda = 2.0$ (increase by 5.3%); $(dp/d\phi)_{\text{max}} = 0.69\ \text{MPa/deg}$ (increase by 17.0%); $\varphi = 30.0^\circ$ (increase by 33.3%); gas-process with EGR 10% - $T_{\text{max}} = 2790\ \text{K}$ (increase by 27.4%); $p_c = 8.1\ \text{MPa}$ (corresponds to diesel fuel); $\lambda = 1.9$ (corresponds to diesel fuel); $(dp/d\phi)_{\text{max}} = 0.60\ \text{MPa/deg}$ (increase by 1.7%); $\varphi = 31.0^\circ$ (increase by 37.8%); gas-process with EGR 20% - $T_{\text{max}} = 2680\ \text{K}$ (increase by 22.4%); $p_c = 7.5\ \text{MPa}$ (decrease by 7.4%); $\lambda = 1.8$ (decrease by 5.3%); $(dp/d\phi)_{\text{max}} = 0.54\ \text{MPa/deg}$ (decrease by 8.5%); $\varphi = 32.0^\circ$ (increase by 6.7%). Max torque: diesel process - $T_{\text{max}} = 2210\ \text{K}$; $p_c = 8.6\ \text{MPa}$; $\lambda = 2.0$; $(dp/d\phi)_{\text{max}} = 0.64\ \text{MPa/deg}$; $\varphi = 20.0^\circ$; gas-process - $T_{\text{max}} = 3050\ \text{K}$ (decrease by 38.0%); $p_c = 11.0\ \text{MPa}$ (decrease by 27.9%); $\lambda = 2.6$ (decrease by 30.0%); $(dp/d\phi)_{\text{max}} = 0.83\ \text{MPa/deg}$ (decrease by 29.7%); $\varphi = 22.0^\circ$ (decrease by 10.0%); gas-process with EGR 10% - $T_{\text{max}} = 2880\ \text{K}$ (decrease by 30.3%); $p_c = 10.2\ \text{MPa}$ (decrease by 18.6%); $\lambda = 2.40$ (decrease by 20.0%); $(dp/d\phi)_{\text{max}} = 0.76\ \text{MPa/deg}$ (decrease by 18.8%); $\varphi = 24.0^\circ$ (decrease by 20.0%); gas-process with EGR 20% - $T_{\text{max}} = 2710\ \text{K}$ (decrease by 22.6%); $p_c = 9.2\ \text{MPa}$ (decrease by 7.0%); $\lambda = 2.32$ (decrease by 16.0%); $(dp/d\phi)_{\text{max}} = 0.66\ \text{MPa/deg}$ (decrease by 3.1%); $\varphi = 23.0^\circ$ (decrease by 15.0%).

5. The translation of the specified diesel fuel oil to natural gas helped to reduce the contents in the exhaust gases when working with EGR 20% of nitrogen oxides by 43.2%, of carbon black in a 5.6 times that of carbon dioxide 33.3%, carbon monoxide by 10.0%.

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