Improving the environmental performance of a diesel engine using natural gas and exhaust gas recirculation

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Abstract. The study of the environmental performance of diesel engines running on natural gas in a wide range of operating conditions is relevant for the further implementation of their transport and transport-technological machines. The paper deals with the use of natural gas as an alternative fuel to improve the environmental performance of a diesel engine. The results of experimental studies on the effect of natural gas and exhaust gas recirculation on the toxicity and smokiness of diesel engine exhaust gases are presented. It is noted that when the diesel engine is running on natural gas with exhaust gas recirculation, the content of nitrogen oxides (NO\textsubscript{x}) in the exhaust gases decreases by 43.2%, soot (C) by 5.6 times, carbon dioxide (CO\textsubscript{2}) by 33.3%, carbon oxides (CO) by 10.0%.

At present, the reduction of air pollution by toxic substances released by industry and road transport is one of the most important problems facing humanity. Air pollution has a harmful effect on humans and the environment [1]. Combustion of the fuel-air mixture in the engine cylinder at high temperatures at local or General lack of oxidizer in the mixture leads to significant pollution of the natural environment with toxic substances and carbon black. The damage caused to the ecological system by pollutants is caused by changes in the concentration of gas components in the atmosphere and the accumulation of particles and chemically active substances in it [2], [3].

The use of alternative energy sources as one of the foundations of promising world energy was a logical result of the historical development and awareness of the need to diversify the primary energy sources used in order to improve the energy and environmental safety of countries, regions and specific energy consumers [4]. In the world, millions of engines are used as power power plants, which generate more than 85% of energy, but consume a huge amount of oxygen and emit hundreds of millions of tons of harmful substances into the atmosphere. Due to the large-scale use of engines, their emissions increase every year, while polluting the environment. Thus, against the backdrop of the inevitable increase in oil prices and the deteriorating environmental situation, primarily due to the increase in the number of engines operating on liquid oil fuel, intensive searches for alternative energy sources are carried out [5], [6].

In Vyatka state agricultural Academy on the basis of the Department of heat engines, cars and tractors conducted research on the transfer of diesel engine 4F 11.0/12.5 to work on natural gas with exhaust gas recirculation (EGR). In order to determine and optimize the main parameters of the diesel engine when operating on natural gas with EGR, its bench tests on diesel, gas-diesel and gas-diesel processes with EGR were carried out. It was found that the diesel operates steadily on natural gas at a ratio of gas (80%), the ignition portion of diesel fuel (20%). As the boot device when testing a diesel engine was used electroharmonix stand SAK-N670 with a pendulum balancing machine. The unit was equipped with the necessary measuring complex. Exhaust gas sampling was carried out by gas intakes
of the ASGA-T system installed on the exhaust pipe of the engine. Exhaust gas opacity was measured using smoke meter «Bosch EFAW-68A» [7], [8].

The content of toxic components in the exhaust gases of the diesel engine 4F 11.0/12.5, depending on the change $\Theta_{inj}$ is shown in figure 1.

Figure 1 shows that when $\Theta_{inj}$ is changed the NO$_x$ content of natural gas with EGR changes according to a similar dependence of the diesel process. With increasing $\Theta_{inj}$ the NO$_x$ increases. When operating a gas diesel engine with EGR 10% ($\Theta_{inj}=26^\circ$), the NO$_x$ content in the exhaust gases is 1300 ppm, which is lower by 21.2% of the gas diesel process. When working on natural gas with EGR 10% ($\Theta_{inj}=23^\circ$), the NO$_x$ content in the exhaust gases is 1100 ppm, which is lower by 24.1% of the gas-diesel process. A further increase in EGR leads to an even greater reduction in nitrogen oxides, but causes an increase in incomplete combustion products. The gas-diesel process is accompanied by an increase in total hydrocarbon emissions (CH$_x$). When operating a diesel engine on natural gas, the content of CH$_x$ in the exhaust gases is 4-5 times higher compared to the diesel process. The concentration of CH$_x$ in a diesel engine running on natural gas with EGR decreases with increasing $\Theta_{inj}$. When operating a gas-diesel engine with EGR 10% ($\Theta_{inj}=26^\circ$), the CH$_x$ content is 0.32%, which is 5.9% lower compared to the gas-diesel process. When working gas diesel engine with EGR 10% ($\Theta_{inj}=23^\circ$) the content of the CH$_x$ equals to 0.36%, lower by 9.9% compared to the gas-diesel process.

Analysis of the soot (C) content in the exhaust gases during the gas-diesel process with the EGR shows that with increasing $\Theta_{inj}$ the soot content practically does not increase. The use of EGR leads to a slight increase in the soot content, while the diesel process significantly increases the soot content. The carbon content of exhaust gases in the gas-diesel process with the EGR is 4-5 times lower than the diesel process.

![Figure 1](image1.png)

**Figure 1.** Regulation characteristic of toxicity of diesel engine 4F 11.0/12.5: — diesel fuel; - - - - - gas-diesel fuel; - - - - - - gas-diesel fuel with EGR 10%; - - - - - gas-diesel fuel with EGR 20%.

![Figure 2](image2.png)

**Figure 2.** Load characteristics of diesel engine toxicity 4F 11.0/12.5: — diesel fuel; - - - - - gas-diesel fuel; - - - - - gas-diesel fuel with EGR 10%; - - - - - gas-diesel fuel with EGR 20%; - - - - - gas-diesel fuel with EGR 30%; - - - - - gas-diesel fuel with EGR 40%.

The content of carbon monoxide (CO) with increasing $\Theta_{inj}$ when working on a gas-diesel process with the EGR also decreases. When working on natural gas with EGR 10% ($\Theta_{inj}=23^\circ$), the CO content
in the exhaust gases is higher by 6.3% of the gas-diesel process, lower by 25.6% of the diesel process. When working on natural gas with EGR, the carbon dioxide (CO$_2$) content decreases with increasing $\Theta$$_{inj}$. When operating a gas diesel with EGR 10% ($\Theta$$_{inj}$=23º), the CO$_2$ content in the exhaust gases is higher by 5.1% of the gas diesel process, lower by 45.4% of the diesel process.

The content of toxic components in the exhaust gases of diesel 4F 11.0/12.5, depending on the load change is shown in figure 2. Figure 2 shows that the use of natural gas leads to an increase in the NO$_x$ content. At the nominal operating mode, this increase is 24.1%, and at $P_e$=0.13 MPa, the NO$_x$ emission increases by 60.5%. The use of EGR reduces the NO$_x$ content throughout the load range. When operating on natural gas with EGR 40% in the load range from 0.13 to 0.26 MPa, the NO$_x$ content is reduced by 63.4%.

When the gas diesel is operating in nominal mode with EGR 10%, the NO$_x$ content is lower by 24.1% of the gas diesel process and corresponds to the diesel process. The use of EGR has a mixed effect on the content of CH$_x$. When working on natural gas with EGR 40% at low loads from 0.13 to 0.26 MPa, there is a decrease in CH$_x$ by 8.7-14.5%, but at $P_e$=0.51 MPa an increase of 42.5%.

The content of soot in the exhaust gases is significantly reduced when working on the gas-diesel process. When working with gas diesel EGR 40% at low loads, the increase in soot content is not more than 5%. The use of EGR on a gas diesel leads to an increase in the CO and CO$_2$ content over the entire load range. When working with EGR 40% at average loads of 0.26 to 0.38 MPa, the CO and CO$_2$ content increases from 12.3 to 17.1% and from 42.2 to 48.8%, respectively. A significant increase in CH$_x$ at high loads is due to incomplete combustion of fuel in the conditions of lack of oxidizer with an increase in EGR.

The content of toxic components in the exhaust gases of diesel engine 4F 11.0/12.5 depending on the change in the speed of the crankshaft is shown in figure 3.

![Figure 3. Speed characteristics of diesel engine toxicity 4F 11.0/12.5](image)

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 min$^{-1}$, the content of 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 CH$_x$ 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 min$^{-1}$ leads to an increase in the CH$_x$ content in the exhaust gases by 6.8 and 4.0 times respectively. 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 CH₄ 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 CO and CO₂ 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 CO₂ 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 CO₂ by 46.0 and 43.6% in relation to the diesel process. Analyzing the content of carbon black in the exhaust gases, we see that with an increase in the rotational speed, the carbon black 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 carbon black 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 carbon black 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%.

Based on the results of studies of the diesel engine 4F 11.0/12.5 proposed to maintain the following ratio: natural gas - 80%, the ignition portion of diesel fuel - 20%.

Recommended for gas-diesel process with EGR as the optimal setting angle of advance of fuel injection equal to 23° to the upper dead point. Since the engine does not have any device for quickly changing the Θ_inj, the same value is recommended for the diesel process.

A promising solution to improve the environmental performance of the diesel engine by using natural gas and EGR is given, which allows reducing the content of nitrogen oxides in the exhaust gases by 43.2%, soot by 5.6 times, carbon dioxide by 33.3%, carbon monoxide by 10.0%.

References
[1] Arent D J, Wise A and Gelman R 2011 Energy Economics 33 584-93
[2] Mohammadi Khoshkar Vandani A and Joda F 2016 Energy Conversion and Management 109 103-12
[3] Dincer I and Zamfirescu C 2016 Journal of Natural Gas Science and Engineering 28 461-78
[4] Osorio-Tejada J L, Llera-Sastresa E and Scarpellini S 2017 Renewable and Sustainable Energy Reviews 71 785-95
[5] Mikulski M and Wierzbicki S 2016 Journal of Natural Gas Science and Engineering 31 525-37
[6] Chai X, Mahajan D and Tonjes D J 2016 Progress in Energy and Combustion Science 56 33-70
[7] Romanyuk V, Likhanov V A and Lopatin O P 2018 Teoreticheskaya i prikladnaya ekologiya 3 doi: 10.25750/1995-4301-2018-3-027-032
[8] Likhanov V A and Lopatin O P 2018 VII Int. Conf. «Modern Technologies for Non-Destructive Testing» IOP Conf. Series: Materials Science and Engineering 457 012011