Optimization of environmental performance of a car diesel engine running on natural gas by reducing carbon black in the exhaust gas

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Abstract. The article considers ways to reduce the soot content in the exhaust gases of motor-tractor diesels (smoke) by using an alternative fuel - compressed natural gas. The influence of gas engine fuel on the parameters of the combustion process and soot content in the cylinder and in the exhaust gases of a high-speed diesel D-245.12C with a dimension of 4CHN 11.0/12.5 (turbocharged, liquid-cooled) is considered. The results of experimental and theoretical studies are presented, which allow us to draw a conclusion about the efficiency and feasibility of using this fuel to reduce the smoke content of exhaust gases.

1. Introduction

Production of diesel engines is one of the priority areas in mechanical engineering, as it provides solutions to a number of problems: scientific and technical, economic, environmental, environmental, and others. Diesels are non-alternative power plants in the automotive, tractor, construction and agricultural engineering industries, and their characteristics ultimately determine the operational, energy, economic, environmental, and mass-dimensional characteristics of the equipment being operated. The production of diesel engines for the Russian armed forces ensures the country's defense capability and is of strategic importance. All specialized rolling stock of road transport used in construction and road management uses diesel engines as power plants.

The global trend to boost internal combustion engines, including diesels, primarily in terms of average effective pressure, leads to an increase in the average cycle temperature and, as a result, an increase in the thermal tension of parts and the content of soot in the exhaust gases. Accordingly, it is necessary to take measures to reduce the thermal load on parts that are directly in contact with hot gases. This, in turn, leads to an increase in heat losses, which negatively affects the efficiency of the engine [1-5].

In addition, internal combustion engines and, in particular, diesels are one of the main sources of air pollution in large cities and consumers of non-renewable hydrocarbon fuels of oil origin. In order to reduce emissions of harmful substances by road transport into the environment, especially in large cities, the Russian Federation has adopted the Concept of developing the Russian automotive industry.
2. Experimental

With the help of the program for determining the mass and relative concentration of soot in the diesel cylinder, we calculated the mass $C$ and relative $r$ of the soot concentration in the turbocharged diesel and gas diesel cylinder (D-245.12C) of dimension 4CHN 11.0/12.5 depending on the angle of rotation of the crankshaft (p.k.v.). The calculation of the soot concentration in the diesel cylinder was carried out using well-known methods developed by professors S. Baturin, A. Loskutov and V. Lozhkin.

For picture 1 shows the change in soot content and temperature in the cylinder of diesel and gas diesel with turbocharged 4CHN 11.0/12.5 depending on the angle of the p.k.v. at the nominal operating mode ($n = 2400 \text{ min}^{-1}, p_e = 0.84 \text{ MPa}$) $\Theta_{\text{vpr}} = 11^\circ \text{p.k.v.}$.

From the presented dependencies, it can be seen that the beginning of visible fuel combustion begins $2...3^\circ$ after the TDC. The ignition of the working mixture leads to intense heat generation, and the gas temperature quickly reaches the maximum value: $2100$ $\text{K}$ for the diesel process and $2500$ $\text{K}$ for the gas-diesel process. The resulting soot content in the exhaust gases consists of two oppositely directed processes - the formation and burning of particles. The predominance of any process in a certain part of the combustion process of the fuel-air mixture leads to a change in the concentration of soot in one direction or another [6-12].

Combustion DT and methane-air mixture (MAM) is characterized as a turbulent flame of a premixed mixture, the combustion processes are realized under conditions of spatial inhomogeneity and non-equilibrium of the fuel distribution in the MAM, instability over time, and taking into account molecular and turbulent diffusion.

The beginning of soot emission in the diesel cylinder coincides with the beginning of visible combustion, that is, soot is formed as soon as a stable flame front appears. The resulting soot content consists of three stages of the soot formation process.

At the first stage, there is a sharp increase in the mass concentration of soot in the diesel cylinder as a result of the predominant influence of the soot formation process over its burnout. In this area, the flame quickly spreads to the entire volume of the mixture prepared for combustion during the ignition delay period (EDP) [13-19].

![Figure 1. Changes in soot content and temperature in the cylinder of a turbocharged diesel engine 4CHN 11.0/12.5 depending on the angle of p.k.v. at $\Theta_{\text{vpr}} = 11^\circ \text{p.k.v.}$; $n = 2400 \text{ min}^{-1}$ and $p_e = 0.84 \text{ MPa}$: - diesel; - - - - - - gas diesel.](image)

Taking into account the research conducted at different times on the study of soot formation mechanisms during the combustion of hydrocarbon fuels, the results of which are currently not in doubt, we assume combustion, that the formation of the main mass of soot particles occurs by a chain radical process and the main ways of soot formation in a turbocharged diesel cylinder when working
on CNG is a low-temperature phenyl mechanism (LTPM) (prevailing in the core of the torch and a temperature of less than 1500 K) and a high-temperature acetylene mechanism (HTAM) (prevailing in the front and a temperature of more than 1500 K) [20-26].

Soot formation occurs mainly in the core of the ignition DT jet as a result of thermal and oxidative pyrolysis of the fuel under conditions of lack of an oxidizer, where the fuel concentration is high and the local excess air coefficient is below the "soot formation threshold". At the initial stage and in the core of the torch, the predominant mechanism of soot formation is LTPM. The rapid expansion of the flame front causes an increase in the amount of fuel burned in this front by the diffusion mechanism, and consequently, a corresponding increase in the mass output of soot. Under conditions of increased charge turbulence, the bulk of the soot produced is carried out of the flame to areas with a relatively low temperature and an excess of oxidizer. In these zones, the oxidation of soot particles begins, but due to the low temperature, the oxidation processes are slowed down and cannot compete with the soot formation processes, so the mass concentration of soot in the cylinder increases rapidly.

At the second stage of the soot formation process, the flame covers a large part of the volume and diffuses the main part of the charge. The temperature in the cylinder increases to the maximum value, and the processes of soot formation and burnout go at comparable speeds, but the total soot content continues to increase. In this area, the main mechanism of soot formation is HTAM. Soot particles formed as a result of physical and chemical transformations of the fuel are oxidized and gasified, since the temperature of the gases becomes high enough, and the overall coefficient of excess air is high [2].

At the third stage, the soot burnout process dominates the formation process. The combustion of the main mass of the charge has been completed by this time, and it is only possible to burn out individual local volumes of the mixture and soot particles. Operation of a turbocharged diesel engine is characterized by a significant depletion of the mixture even at high load conditions and increased turbulence of the mixture in the engine cylinder. That is, favorable conditions are created for burning out soot particles. This process lasts until the exhaust valves are opened, and the soot content is reduced to values that determine the smoke content of the exhaust gases.

The main factors that influence the formation and combustion of soot in the cylinder are the values of \( T_{\text{max}} \), \( p_{z,\text{max}} \) of the cycle, the residence time of particles in the reaction zone, and the excess air coefficient \( \alpha \). The rate of soot burnout is determined by the rates of chemical reactions on the surface of the particles. The temperature of the combustion products and the concentration of oxygen in them have a combined effect on the rate of soot burnout. Taking into account that methane is the least prone to soot formation of hydrocarbons and the presence of turbocharging, which provides increased density and turbulence of the charge, it is possible to explain the minimum level of smokiness of diesel exhaust when working on CNG.

When working with a diesel process, the mass concentration of soot reaches its maximum of 0.33 g/m³ after 15° p.k.v. after the TDC, then it begins to decrease, reaching the value of 0.11 g/m³ by the time the exhaust valve is opened, i.e. it is reduced by 3 times.

When working with a gas-diesel process, \( C_{\text{max}} = 0.23 \) g/m³, and by the time the exhaust valve is opened, it is only 0.03 g/m³, i.e. it is reduced by 7.7 times.

When working with a diesel process, the maximum relative concentration of soot is 0.133 g/kg, and by the time the exhaust valve is opened, it is already 0.044 g/kg, i.e. the reduction is 66.9 %.

The amount of soot particles in the unit of the reaction volume and their size have a strong influence on the emissivity and radiation emission of the flame. When performing calculations to determine the number of N soot particles per unit volume, we made the following assumptions:

- The polydisperse system of soot particles is represented by a monodisperse system with an equivalent modal particle radius of 20 nm.
- The density of soot particles does not depend on the formation mechanism and is 1.9 g/cm³.
Based on these assumptions, the estimated maximum amount of particulate matter is $5.2 \cdot 10^6$ in mm$^3$ for the diesel process and $3.6 \cdot 10^6$ in mm$^3$ for the gas-diesel process. After reaching the maximum when the crankshaft is rotated further, the amount of soot particles decreases in proportion to the decrease in mass concentration. By the time the exhaust valve is opened in the diesel process, the number of soot particles $N$ is already $1.7 \cdot 10^6$ in mm$^3$, i.e. it is reduced by 67 %, and in the gas-diesel process, the number of soot particles $N$ is $0.4 \cdot 10^6$ in mm$^3$, i.e. it is reduced by 88.9 % [27-33].

3. Conclusion
The results obtained allow us to speak about the efficiency of using CNG as a motor fuel in a turbocharged diesel engine in order to reduce the smoke content of the exhaust gases and, consequently, the soot content in the exhaust gas. It should be noted that the specified diesel D-245.12C in terms of exhaust smoke corresponds to the Euro-1 standards, and its gas-diesel modification with a significant margin meets the Euro-4 standards.

At the same time, when switching to the gas-diesel process, the content of unburned CH hydrocarbons and carbon dioxide CO$_2$ in the exhaust gases increases. Reducing the CH content in the exhaust gases can be achieved by installing a catalytic Converter, and CO$_2$ is a product of complete combustion of fuel, non-toxic, although it belongs to the gases that cause the «greenhouse effect».

That is, the combustion of natural gas in a cylinder of a turbocharged diesel engine improves the calorific value of the fuel and the rate of combustion of the air-fuel mixture, and therefore the maximum cycle temperature $T_{\text{max}}$ and maximum gas pressure $p_{\text{z,max}}$ in the cylinder. However, on the other hand, this leads to an increase in the rigidity of the combustion process and the load on the parts of the CNG. Therefore, the installation of an earlier UOV'T is not recommended due to the overly rigid operation of the engine. The installation of a later than the optimal UOV'T leads to a shift of the combustion process to the right of the TDC and deformation of the engine.

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