Calculation of the soot content in the diesel cylinder with turbocharge 4CHN 11,0/12,5 when working on natural gas

V A Likhanov and A V Rossokhin
Department of thermal engines, automobiles and tractors, Vyatka State Agricultural Academy, 610017, Kirov, October prospect, 133, Russian Federation

E-mail: Rossokhin.dvs@mail.ru

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
Internal combustion engines (ICE) and, in particular, diesel engines are one of the main sources of air pollution in large cities and consumers of non-renewable hydrocarbon fuels of petroleum origin. A significant hazard to human health is benz(α)pyrene adsorbed on the surface of soot particles. Reducing emissions of soot with exhaust gases (EG) of diesel engines will reduce the emissions of benz(α)pyrene into the environment and its negative impact on people and animals. Since the formation of benz(α)pyrene is an integral part of the soot formation process, a decrease in the soot content in the exhaust gas will lead to a proportional decrease in the benz(α)pyrene C_{20}H_{12} [1]. Moreover, according to experts, the most promising fuel both in terms of reserves and in terms of low cost and environmental friendliness is compressed natural gas (CNG).

The fundamental issue when creating an internal combustion engine is to reduce the content of nitrogen oxides and soot in the exhaust gas, especially diesel engines. Perhaps in the future a similar problem can be solved by the creation and widespread use of purely gas engines. However, at the transitional stage, the creation of gas diesel engines based on existing and produced diesel engines is equally important. This will allow to create environmentally friendly engines without investing significant material costs and significantly save and replace fuel of petroleum origin, while ensuring dual-fuel diesel and thereby expand its scope [2].

Having analyzed earlier research work on reducing diesel smoke by using natural gas as a motor fuel, it should be noted that there is no study of the effect of combined use of natural gas and turbocharging on efficient and environmental performance of diesel engines, a small number of works on the use of natural gas in turbocharged car diesel engines with a displacement of up to 5 liters. Few works brought to the creation of prototypes and passed operational tests [3]. All of the above gives reason to believe that improving the environmental performance of automotive diesel engines by reducing exhaust smoke with the combined use of natural gas and turbocharging,
improving the efficient performance of diesel engines, replacing and saving motor fuel of petroleum origin is an urgent scientific task that is essential for engine building and requires timely solutions, including for engines with a working volume of up to 5 liters.

2. Experimental

Currently, the need has arisen for the transfer of gaseous fuels to automotive diesel engines, including those with turbocharging, with a working volume of up to 5 liters. And the continuation of these works was the creation of a gas-diesel modification of a turbocharged automotive diesel engine manufactured by MMZ D-245.12C. This engine is installed on ZIL-5301 cars, and its modifications on PAZ buses. The nominal diesel power is 80 kW at a speed of n = 2400 min\(^{-1}\), the engine complies with Euro-1, the minimum specific effective fuel consumption of 218 g/(kWh), the installation angle of advance of fuel injection (UOVT) - 11° p.k.v. The created gas-diesel modification retains its rated power, while the ignition fuel consumption is about 3 kg/h and gas consumption is 14 kg/h, the minimum specific effective fuel consumption is reduced to 208...210 g/(kWh). Natural gas is supplied to the intake manifold through a specially designed metering mixer in front of the turbocharger. The CNG supply control system includes a mechanism for fixing the injection pump rail when setting the value of the ignition diesel engine when switching to gas and the system of electromagnetic valves [5, 6].

Bench tests of diesel engines were carried out in accordance with GOST 14846-81 «Automobile engines. Bench Test Methods» and the developed methodology, which includes taking effective and environmental indicators, indicating the workflow, and developing zone and mathematical models for the formation and burning of soot in a turbocharged diesel engine when using natural gas [6, 7]. The calculation of the soot concentration in the diesel cylinder was carried out according to well-known methods developed by professors S. Baturin, A. Loskutov and V. Lozhkin [8, 9, 10].

To determine the amount of soot formed during fuel combustion, the concepts of mass C soot concentration, relative r soot concentration and the number of soot particles N soot per unit volume in the diesel cylinder are used.

Based on the Bouguer-Beer law, the actual dimensional concentration C with a gray radiation pattern can be expressed in terms of the relative concentration

\[ C = \frac{r}{M} \]  

where M is the Bouguer number, for the experimental conditions M = const.

Therefore, the relative concentration r is always proportional to the actual mass C and is determined only by the degree of attenuation of the beam in the diesel cylinder, i.e.

\[ r = MC = \ln\left(\frac{I_0}{I_e}\right), \]  

where \( I_0 \) and \( I_e \) are the initial beam intensities and after passing through the cylinder.

Thus, the parameter r characterizes a qualitative change in the actual concentration caused by the formation of soot, its burnout, and a change in the volume of the cylinder.

In order to evaluate the change in the carbon black content caused only by the volumetric carbon black process, it is necessary to exclude the influence of the variable cylinder volume on the resulting carbon black concentration. At known concentrations C and r, the mass soot content in the cylinder at a certain point in time, which corresponds to the cylinder volume \( V_i \), is defined as

\[ rV_i = MCV \]  

Choosing a unit volume \( V_0 \) as the reduction volume, we obtain

\[ r = MN, \]  

where \( r = \overline{C}\left(V_i/V_0\right) \) is the relative soot content in the cylinder at a conditionally constant volume \( V_c = V_0 \).
\[ r = C\left(\frac{V_i}{V_0}\right) \]  - absolute carbon black content in the cylinder at a conditionally constant volume \( V_c = V_0 \).

In figure 1 presents the maximum values of the soot content and the maximum temperature in the engine cylinder depending on the load at \( \Theta_{vpr} = 11^\circ \) p.k.v. when working on diesel and gas-diesel processes at \( n = 2400 \text{ min}^{-1} \) [3-8].

With an increase in load at a rotational speed of \( n = 2400 \text{ min}^{-1} \), an increase in the soot content in the exhaust gas and in the cycle temperature occur. This is due to an increase in the cyclic supply of fuel, but with increasing temperature, the rate of oxidation of soot particles increases and, accordingly, the share of burnable soot. High charge turbulization and excess air coefficient allow to reduce the soot content in diesel exhaust gas to Euro-2 standards, and gas diesel to Euro-4 standards.

Based on the results obtained, it can be concluded that the use of natural gas can reduce the soot content in the cylinder over the entire range of load changes.

![Figure 1. Changes in carbon black content and temperature in the cylinder 4CHN 11,0/12,5 turbocharged diesel engine, depending on load changes at \( \Theta_{vpr} = 11^\circ \) p.k.v. and \( n = 2400 \text{ min}^{-1} \): - diesel; - - - - - gas diesel.](image1)

In figure 2 presents a change in the indicators of carbon black and temperature in the cylinder of a diesel engine depending on the speed at \( \Theta_{vpr} = 11^\circ \) p.k.v. and work on diesel and gas-diesel processes.

With increasing speed, the maximum temperature of the cycle and the maximum carbon black content in the cylinder of a turbocharged diesel engine increase. At a low rotational speed, the maximum mass soot content is lower, since the time period devoted to the oxidation of soot particles increases, although the soot formation intensity is maximum at temperatures below 2000 K. With increasing speed and increasing cycle temperature, the maximum mass content of soot increases. It should be noted that the maximum values of soot content during operation of the gas-diesel process are below the similar values of the diesel process at all considered speed modes.

The maximum relative concentration of soot in the diesel cylinder when operating on natural gas is also below the similar values of the diesel process [9-14].

The maximum number of soot particles per unit volume in the engine cylinder, respectively, also increases with increasing speed, which is associated with an increase in the maximum mass concentration of soot in the cylinder.
The most important factors and parameters of soot particles include particle dispersion (size and particle size distribution function), thermal and dynamic nonequilibrium associated with particles in the stream, and optical properties of the particle material.

The need for such studies is due not only to a lack of information, but also to the rigorous binding of the results to the conditions of the experiment, which casts doubt on the possibility of using this information in further correct calculations [15-20].

The complex dependence of soot particle sizes on a large number of factors was not reflected in any generalized theory of particle size changes in an engine. Based on the considered works, however, it is not possible to draw definite quantitative conclusions about the effect of combustion conditions on the particle size spectrum of soot formed in a cylinder in a flame during the combustion of liquid fuel and gas.

Sizing of soot particles to this day remains a difficult scientific and technical task. The analysis of literature showed that the data on the determination of particle sizes are not systematic and often contradictory.

The issue of soot formation in diesel engines has been the subject of a large number of works that touch upon the mechanism of soot formation, its structure, thermodynamic and thermophysical properties [19]. At the same time, works on the formation of soot in gas-diesel cylinders and determination of the distribution of soot particles in exhaust gases by size is extremely small [21-33].

The structure of soot particles and the particle size distribution depend on temperature, on the ratio of C and H atoms and are determined by the processes preceding the formation of soot particles.

The results of work carried out in CCTI, MSTU. N.E. Bauman and analysis of the available size distribution curves of soot particles [11, 15, 28] showed that all of them are satisfactorily described by a dependence similar to the Maxwell distribution, which is close to normal. Denoting N(x) the probability density distribution characterizing the dispersed composition of soot particles, we can write:

\[ N(x) = Ax^2 e^{-bx^2} \]
After the necessary mathematical transformations, we obtain the following expression

\[ N(x) = \frac{4}{\sqrt{\pi} x_m} \sum(z) \]  \hspace{1cm} (6)

The calculations showed that equation (6) well describes the available experimental data on the size distribution of soot carbon particles.

A characteristic feature of equation (6) is that the particle size spectrum for any distribution is uniquely determined by only one parameter - the most probable (modal) particle size \( x_m \) for the universal function \( \Sigma(z) \) for all distributions.

To compare different particle size distributions, it is convenient to use the dependence expressed in dimensionless coordinates

\[ \hat{N}\left(\frac{x}{x_m}\right) = \frac{N(x)}{N(x_m)} = \left(\frac{x}{x_m}\right)^2 e^{-\left[\left(\frac{x}{x_m}\right)^2-1\right]} \]  \hspace{1cm} (7)

Using the generalized equation (7), it is not difficult to determine any averaged characteristic of the particle size spectrum of soot carbon in the flame as the mathematical expectation of certain average values.

Solving additional equations and substituting the values of the possible sizes of soot particles in equation (6), and using the calculated values obtained, we construct a graph of the probability density distribution \( N(x) \).

3. Conclusion
Summing up the results of experimental and computational studies on the effect of the use of CNG as a motor fuel in a 4CHN 11,0/12,5 turbocharged diesel engine, we can say that the combined use of natural gas and turbo-blowing can significantly reduce the carbon black content in the exhaust gas, and thereby to improve the environmental performance of the diesel 4CHN 11,0/12,5 (D-245.12C) by reducing exhaust smoke.

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