Influence use of methanol in the engine on content nitrogen oxides and soot in the exhaust gases

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Abstract. The article presents the advantages of using methyl alcohol on tractor diesel compared with traditional hydrocarbon fuel of petroleum origin. The potential effect of methyl alcohol is considered when it is burned directly in a diesel cylinder with an ignition portion of diesel fuel when working with a dual fuel supply system, depending on various installation angles of advancing fuel injection on emissions of harmful substances with exhaust gases.

Nitrogen oxides (NO) are formed during combustion in a combustion chamber (CS) of a diesel engine at various concentrations. According to some authors, chain reactions begin with the appearance of atomic oxygen, which is formed as a result of the dissociation of oxygen molecules at high temperatures achieved during combustion. In accordance with this mechanism, nitrogen atoms do not start a chain reaction, since their equilibrium concentration during combustion is relatively low compared to the equilibrium concentration of atomic oxygen. Therefore, during combustion in a diesel cylinder, the formation of NO is associated with local concentrations of oxygen atoms and temperature.

NO is not generated in the diesel cylinder during the compression stroke due to the relatively low temperature reached. Although NO does not form in the zones of poor flameout in the early stages of combustion, an increase in temperature can cause combustion in these zones, and the formation of NO will occur later, after the remainder of the jet burns [1,2].

The rate of NO formation is higher in the flame of rich mixtures than in stoichiometric or poor ones. However, the final concentration is maximum for mixtures that are slightly poorer than stoichiometric. The combustion zones of the lean mixture are one of the main zones of NO formation, since this part burns first and has the longest residence time after the flame zone.

An increase in temperature due to combustion in the core and on the cylinder walls can increase the formation of NO in two ways. Firstly, an increase in the average temperature in the cylinder, leading to an increase in the concentration of NO in the combustion zones of the lean mixture and the breakdown of the poor flame, as well as in the remaining air. Secondly, this can lead to a very high flame temperature in the core of the fuel flame. The amount of NO produced in the core also depends on the local oxygen concentration. When fuel is supplied through a larger number of nozzle openings, the oxygen concentration in the core increases, which leads to an increase in NO [3-5].

When the temperature decreases during the expansion course, the NO concentration does not decrease to equilibrium concentration. It was found that in piston engines the process of NO disappearance during expansion is very slow, therefore, the NO concentration in this stroke does not
change. This is especially true for the burning of poor mixtures. Therefore, an increase in the fuel-air ratio leads to an increase in the maximum mass-average gas temperature, as evidenced by an increase in the maximum pressure and temperature of the exhaust gas. An increase in the maximum mass average gas temperature is not accompanied by a corresponding increase in the amount of NO. This confirms the fact that NO emissions from direct injection engines are mainly associated with combustion in areas of lean mixture; in addition, the concentration of NO due to subsequent combustion of the fuel in the core and on the walls may not be the main source of NO formation [6].

The combustion of hydrocarbon fuels is usually accompanied by the formation of soot particles in the flame. This phenomenon is easily detected visually: by the luminosity of the flame and smoke. However, to date, the mechanism of soot formation during combustion has not been fully investigated, which is explained by the extreme complexity of this physicochemical process, which takes about 10-3 ... 10-2 s.

A significant number of works have been devoted to the study of the physicochemical properties of soot particles [7].

Researchers’ interest in this issue is explained, on the one hand, by the widespread use and production of soot in industry, and, on the other hand, by the desire to penetrate into the mechanisms of processes that determine the carbon emission in flames. Thanks to the use of modern research methods, such as high-resolution electron microscopy, fluoroscopy and spectroscopy, gas chromatography, etc., a fairly complete picture of the size, structure, and physicochemical properties of soot particles has been obtained in the last decade [8,9].

The researchers found that in flames, the particle size of soot, depending on the conditions for the organization of fuel combustion, can vary approximately from 1 to 1000 nm. The minimum particle size of carbon black (of the order of 1.0 ... 1.5 nm) is established on the basis of electron microscopic studies. Such particles have about 600 ... 2000 atomic mass units, i.e. include approximately 50 ... 160 carbon atoms.

An analysis of electron micrographs for various combustion conditions revealed a wide range of forms of soot particles: spherical or almost spherical particles, chain-shaped, flocculent, lace-like and other structures. In this case, the conditions for the selection and deposition of particles could have a certain effect, but the presence of soot particles of various shapes in the products of combustion is also confirmed by optical measurements. For most practically important schemes for organizing the combustion of hydrocarbon fuels, including for the conditions of diesel combustion chambers, it has been established that the basis for the structure of soot particles is spherical particles with a diameter of about 20 ... 40 nm. Complex structures, as a rule, are secondary, formed as a result of coagulation of primary spherical particles [10-13].

Chemical analysis of soot shows that it contains 94 ... 99% carbon and 0.5 ... 3.0% hydrogen by weight, as well as a certain amount of oxygen and ash elements. The atomic C / H ratio varies from 3 to 15. Consequently, soot can be considered as a solid hydrocarbon or carbonaceous substance, and the terms “solid carbon” and “dispersed carbon” are not entirely accurate. Soot particles are richer in hydrogen in the early stages of flame formation and growth. So, carbon black particles with a diameter of 1.5 nm have an atomic ratio C / H = 3. It should also be noted that, according to research by many authors, carbon black particles have radical properties that are characteristic, first of all, of particles formed at earlier stages the process of soot formation. The density of soot particles depending on the hydrogen content varies within $\rho_c = (1.8 ... 2.0) \times 103$ kg / m$^3$.

Figure 1a, shows the graphs of the effect of methanol use in a 2H 10.5 / 12.0 diesel engine when working with a dual fuel supply system (DFSS) at various installation angles of advancing fuel injection (AAFI) on the content of nitrogen oxides in exhaust gases (EG) engine speed (n = 1800 min$^{-1}$), taken at $\Theta_{df} = (26 ... 42^\circ)$ and $\Theta_m = (22 ... 38^\circ)$. If, at the optimum values of the installation AAFI ($\Theta_{df} = 34^\circ$ and $\Theta_m = 34^\circ$), the content of nitrogen oxides in the diesel exhaust gas is 340 ppm, then with a larger value of $\Theta_m = 38^\circ$ the content of nitrogen oxides in the exhaust gas increases and amounts to 390 ppm. For other values of $\Theta_m = 30^\circ, 26^\circ$ and $22^\circ$, the content of nitrogen oxides in the exhaust gas is 347 ppm, 348 ppm and 220 ppm, respectively [14-16].
The curves of changes in the values of the content of nitrogen oxides in the exhaust gas of a diesel engine, obtained with the installation AAFI Θ_{g1} = 26^º and different angles of injection of methanol Θ_{m1}, show that with the installation AAFI Θ_{m1} equal to 34^º, 30^º, 26^º and 22^º, the content of nitrogen oxides in the exhaust gas is, respectively, 365 ppm, 350 ppm, 300 ppm and 225 ppm.

The values of the nitrogen oxide content in the diesel exhaust gas obtained with the installation AAFI Θ_{g1} = 30^º and different injection angles of methanol Θ_{m1} show that with the installation AAFI Θ_{m1} equal to 34^º, 30^º, 26^º and 22^º, the nitrogen oxide content in the exhaust gas is 355 ppm, respectively, 340 ppm, 290 ppm and 230 ppm. It can be seen from the graph that, with an increase in the angle of rotation AAFI Θ_{m1}, the content of nitrogen oxides in the exhaust gas of a diesel engine changes in a complex relationship.

Changes in the values of the nitrogen oxide content in the diesel exhaust gas obtained with the installation AAFI Θ_{g1} = 38^º and different injection angles of methanol Θ_{m1} show that with the installation AAFI Θ_{m1} equal to 38^º, 34^º, 30^º, 26^º and 22^º, the content of nitrogen oxides in the exhaust gas is equal to respectively, 273 ppm, 310 ppm, 349 ppm, 330 ppm and 215 ppm. The graph shows that the trend in the values of the content of nitrogen oxides in the exhaust gas of a diesel engine occurs in a complex relationship with an increase in the angle of the AAFI Θ_{m1}.

The curves of changes in the values of the content of nitrogen oxides in the exhaust gas of a diesel engine, obtained with the installation AAFI Θ_{g1} = 42^º and different angles of injection of methanol Θ_{m1}, show that with the installation AAFI Θ_{m1} equal to 38^º, 34^º, 30^º, 26^º and 22^º, the content of nitrogen oxides in the exhaust gas is equal to respectively, 273 ppm, 310 ppm, 349 ppm, 330 ppm and 215 ppm. The graph shows that the trend in the values of the content of nitrogen oxides in the exhaust gas by a complex dependence with an increase in the angle of the AAFI Θ_{m1} also remains [17-20].

Figure 1. The effect of the use of methanol in a 2H 10.5 / 12.0 diesel engine when working with DFSS, depending on various installations AAFI, on the content of nitrogen oxides in the exhaust gas: a - at n = 1800 min\(^{-1}\) and p_c = 0.585 MPa, q_{\text{c,df}} = 6.6 mg / cycle; b - at n = 1400 min\(^{-1}\) and p_c = 0.594 MPa, q_{\text{c,df}} = 6.0 mg / cycle.

Figure 1b, shows the graphs of the effect of methanol use in a 2H 10.5 / 12.0 diesel engine when working with DFSS with various installation AAFI on the content of nitrogen oxides in the exhaust gas at the engine speed (n = 1400 min\(^{-1}\)), taken at Θ_{g1} (26 ... 42^º) and Θ_{m1} (22 ... 38^º).

If, at the optimum values of the installation AAFI (Θ_{g1} = 34^º and Θ_{m1} = 34^º), the content of nitrogen oxides in the exhaust gas of a diesel engine is 360 ppm, then with a larger value of Θ_{m1} = 38^º the content of nitrogen oxides in the exhaust gas increases and amounts to 410 ppm. For other values of Θ_{m1} = 30^º, 26^º and 22^º, the content of nitrogen oxides in the exhaust gas is 367 ppm, 368 ppm, and 240 ppm, respectively. The curves of changes in the values of the content of nitrogen oxides in the exhaust
gas of a diesel engine, obtained with the installation AAFI $\Theta_{df} = 26^\circ$ and different angles of injection of methanol $\Theta_m$, show that with the installation AAFI $\Theta_m$ equal to 34°, 30°, 26° and 22°, the content of nitrogen oxides in the exhaust gas is, respectively, 385 ppm, 370 ppm, 320 ppm and 245 ppm.

The values of the nitrogen oxides content in the diesel exhaust gas obtained with the installation AAFI $\Theta_{df} = 30^\circ$ and various injection angles of methanol $\Theta_m$ show that with the installation AAFI $\Theta_m$ equal to 34°, 30°, 26° and 22°, the content of nitrogen oxides in the exhaust gas is equal, respectively, 360 ppm, 310 ppm and 250 ppm. It can be seen from the graph that with an increase in the installation AAFI $\Theta_m$, the content of nitrogen oxides in the exhaust gas of a diesel engine changes in a complex relationship [21-23].

Changes in the values of the nitrogen oxide content in the diesel exhaust gas, obtained with the installation AAFI $\Theta_{df} = 38^\circ$ and different injection angles of methanol $\Theta_m$, show that with the installation AAFI $\Theta_m$ equal to 38°, 34°, 30°, 26° and 22°, the content of nitrogen oxides in the exhaust gas is equal, respectively, 375 ppm, 345 ppm, 315 ppm, 275 ppm and 235 ppm. The graph shows that with an increase in the installation AAFI $\Theta_m$ is still maintained.

The curves of changes in the values of the content of nitrogen oxides in the exhaust gas of a diesel engine, obtained with the installation AAFI $\Theta_{df} = 42^\circ$ and different angles of injection of methanol $\Theta_m$, show that with the installation AAFI $\Theta_m$ equal to 38°, 34°, 30°, 26° and 22°, the content of nitrogen oxides in the exhaust gas is equal, respectively, 295 ppm, 330 ppm, 370 ppm, 350 ppm and 235 ppm. It can be seen from the graph that the trend in the values of the content of nitrogen oxides in the exhaust gas with an increase in the angle of the AAFI $\Theta_m$ remains unchanged.

Figure 2a, shows the dependence of the change in the smoke of an exhaust gas of a diesel engine $2H 10.5 / 12.0$ when working with DFSS at various installation of AAFI DF and methanol in the nominal operating mode at $n = 1800 \text{ min}^{-1}$. It can be seen from the graph that with an increase in the installation AAFI of methanol from $\Theta_m = 22^\circ$ to $\Theta_m = 38^\circ$, the exhaust smoke decreases over the entire range of the installation of the AAFI DF.

Considering the smoke of the exhaust gas when working on methanol with DFSS with the installation of the AAFI DF $\Theta_{df} = 26^\circ$, the following can be noted. With an increase in the methanol AAFI installation, the exhaust smoke decreases from 1.7 units on the Bosch scale with $\Theta_m = 22^\circ$ up to 1.1 units on the Bosch scale with $\Theta_m = 34^\circ$. The decrease is 0.6 units on a Bosch scale or 35.3%. With an increase in the installation AAFI DF to $\Theta_{df} = 30^\circ$, the exhaust smoke changes from 1.6 units with $\Theta_m = 22^\circ$ to 0.95 units on the Bosch scale with $\Theta_m = 34^\circ$, i.e. reduced by 40.0%.

Considering the smoke of the exhaust gas when working on methanol with DFSS with the installation of the AAFI DF $\Theta_{df} = 34^\circ$, it is clear that the exhaust smoke varies from 1.45 units on the Bosch scale with $\Theta_m = 22^\circ$ up to 0.8 units on the Bosch scale with $\Theta_m = 38^\circ$. The decrease is 0.65 units on the Bosch scale or 31.0%. With an increase in the installation AAFI DF to $\Theta_{df} = 38^\circ$, the exhaust smoke decreases from 1.3 units on the Bosch scale with $\Theta_m = 22^\circ$ up to 0.8 units on the Bosch scale with $\Theta_m = 38^\circ$, i.e. 0.5 units on the Bosch scale or by 38.4%. When you change the installation AAFI DF to $\Theta_{df} = 42^\circ$, the exhaust smoke decreases from 1.1 units on the Bosch scale with $\Theta_m = 22^\circ$ up to 0.8 units on the Bosch scale with $\Theta_m = 38^\circ$, i.e. by 27.3%.

Considering the exhaust smoke when working on methanol with DFSS with the installation of methanol AAFI $\Theta_m = 22^\circ$, the following can be noted. With an increase in the installation of the DFSS DF, the exhaust smoke decreases from 1.7 units on the Bosch scale with $\Theta_{df} = 26^\circ$ to 1.1 units on the Bosch scale with $\Theta_{df} = 26^\circ$. The decrease is 0.6 units on a Bosch scale or 35.3%. With an increase in the installation AAFI of methanol $\Theta_m = 26^\circ$, the exhaust gas smoke changes from 1.6 units with $\Theta_{df} = 26^\circ$ to 1.0 units on the Bosch scale with $\Theta_{df} = 26^\circ$, i.e. reduced by 0.6 units on the Bosch scale. With the installation of methanol AAFI $\Theta_m = 30^\circ$, the exhaust smoke decreases from 1.5 units with $\Theta_{df} = 26^\circ$ to 0.9 units on the Bosch scale with $\Theta_{df} = 26^\circ$, i.e. by 40.0%.

With an increase in the installation AAFI of methanol $\Theta_m = 34^\circ$, the exhaust smoke decreases from 1.1 units on the Bosch scale with $\Theta_{df} = 26^\circ$ to 0.8 units according to the Bosch scale at $\Theta_{df} = 42^\circ$, while the minimum value is reached already with the installation of the AAFI $\Theta_{df} = 34^\circ$. The decrease is 0.3
units on a Bosch scale or 27.3%. With the installation of the AAFI of methanol Θ_m = 38º it is seen that the exhaust smoke does not change and is equal to 0.8 units on the Bosch scale on all installation AAFI DF [24].

Figure 2. The effect of the use of methanol on the smokiness of the exhaust gas of a diesel engine 2H 10.5 / 12.0 when working with DFSS with various installations AAFI: a - at n = 1800 min⁻¹ and p_e = 0.585 MPa, q_cdf = 6.6 mg / cycle; b - at n = 1400 min⁻¹ and p_e = 0.594 MPa, q_cdf = 6.0 mg / cycle.

With an increase in the installation AAFI of methanol Θ_m = 34º, the exhaust smoke decreases from 1.1 units on the Bosch scale with Θ_df = 26º to 0.8 units according to the Bosch scale at Θ_df = 42º, while the minimum value is reached already with the installation of the AAFI Θ_df = 34º. The decrease is 0.3 units on a Bosch scale or 27.3%. With the installation of the AAFI of methanol Θ_m = 38º it is seen that the exhaust smoke does not change and is equal to 0.8 units on the Bosch scale on all installation AAFI DF.

Thus, on the basis of the obtained data, the minimum value of the exhaust smoke is observed when the installation AAFI of methanol changes from Θ_m = 34º to Θ_m = 38º, and DF from Θ_df = 34º to Θ_df = 42º.

Figure 2b, shows the dependence of the change in the smoke of an exhaust gas of a diesel engine 2H 10.5 / 12.0 for various installation of AAFI and methanol at maximum torque at n = 1400 min⁻¹. It can be seen from the graph that an increase in the installed AAFI of DF and methanol leads to a decrease in exhaust smoke.

Considering the smoke of the exhaust gas when working on methanol with DFSS with the installation of the AAFI Θ_m = 22º, the following can be noted. With an increase in the installation of the AAFI DF, the exhaust smoke value decreases from 1.3 units on the Bosch scale with Θ_df = 26º to 1.0 units on the Bosch scale with Θ_df = 42º, i.e. by 30%. With the installation of the AAFI of methanol Θ_m = 26º, the exhaust smoke varies from 1.2 units on the Bosch scale with Θ_df = 26º to 0.8 units on the Bosch scale with Θ_df = 42º. With an increase in the installation AAFI of methanol to Θ_m = 30º, the exhaust smoke decreases from 1.0 unit on the Bosch scale with Θ_df = 26º to 0.8 units on the Bosch scale with Θ_df = 42º. With an increase in the methanol AAFI installation Θ_m = 34º, the exhaust smoke changes from 0.9 on the Bosch scale with Θ_df = 26º to 0.8 units on the Bosch scale with Θ_df = 42º. While the minimum value is achieved when Θ_df = 34º, the reduction of smoke is 0.1 units on a Bosch scale or 11%. With the installation of methanol AAFI Θ_m = 38º, the smokiness practically does not change and is equal to 0.8 units on the Bosch scale [25].

Considering the exhaust smoke when working on methanol with DFSS with the installation of AAFI DF Θ_df = 26º it is seen that with an increase in the installation of AAFI of methanol, the value of exhaust smoke decreases from 1.3 units on the Bosch scale with Θ_m = 22º to 0.9 units on the Bosch
scale with $\Theta_m = 34^\circ$. With a change in the installation AAFI DF $\Theta_{df} = 30^\circ$, the exhaust smoke decreases from 1.2 units on the Bosch scale with $\Theta_m = 22^\circ$ to 0.8 units on the Bosch scale with $\Theta_m = 34^\circ$. With an increase in the installation of the AAFI DF $\Theta_{df} = 34^\circ$, the exhaust smoke decreases from 1.05 units with $\Theta_m = 22^\circ$ to 0.8 units on the Bosch scale with $\Theta_m = 38^\circ$. In this case, the minimum value is achieved when $\Theta_m = 34^\circ$. With the installation of the AAFI DF $\Theta_{df} = 38^\circ$, the exhaust smoke decreases from 1.0 unit with $\Theta_m = 22^\circ$ to 0.8 units on the Bosch scale with $\Theta_m = 38^\circ$. With an increase in the installation AAFI DF $\Theta_{df} = 42^\circ$, the smokiness changes from 1 unit on the Bosch scale with $\Theta_m = 22^\circ$ up to 0.8 units on the Bosch scale with $\Theta_m = 38^\circ$.

Such low values of exhaust smoke are explained by the fact that methanol has a lower tendency to smoke formation than diesel fuel. The value of exhaust smoke when working on methanol with DFSS is due to the presence of an ignition portion of diesel fuel.

Thus, on the basis of the data obtained, the minimum value of the exhaust smoke is observed with the installation AAFI of methanol $\Theta_m = 34^\circ$ and $\Theta_m = 38^\circ$. Analyzing the data obtained, the combination of the installation AAFI DF $\Theta_{df} = 34^\circ$ and methanol $\Theta_m = 34^\circ$ is taken as optimal in the nominal mode and the maximum torque mode.

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