Influence of ethanol on the combustion process and soot formation in the diesel cylinder

A N Kozlov, A A Anfilatov and A N Chuvashev
Department of thermal engines, automobiles and tractors, Vyatka State Agricultural Academy, 610017, Kirov, October prospect, 133, Russian Federation

Abstract. Ethanol is an attractive alternative fuel because it is a renewable bio-based resource and it is oxygenated, thereby providing the potential to reduce particulate emissions in compression-ignition engines. Thus, the use of ethanol in a diesel engine can simultaneously solve two important problems - the replacement of non-renewable diesel fuel and improving the environmental performance of diesel by reducing soot emissions into the atmosphere. Thus, the use of ethanol in a diesel engine can simultaneously solve two important problems - the replacement of non-renewable diesel fuel and improving the environmental performance of diesel by reducing soot emissions into the atmosphere. The presented work considers the main reasons for reducing the formation of solid particles in the diesel cylinder, taking into account the transformation of the combustion process. The article presents the results of experimental studies to reduce the soot content in the exhaust gases by direct injection of ethanol into the combustion chamber with ignition from the burning fuel jet. The implementation of this method somewhat complicates the design of the diesel engine but allows you to control the combustion process and exclude the maximum amount of diesel fuel. The characteristics of the combustion process of alternative fuels in the diesel cylinder and the main patterns of change are described. In conclusion, the main problems of the use of ethanol and promising directions of its use as a fuel for the engine with compression ignition are considered, taking into account the peculiarities of the combustion process and the formation of harmful components of exhaust gases.

The most common biofuel in the world is bioethanol, which accounts for 82% of the world's biofuel production. A wide range of raw materials of the food and processing industry is able to ensure the production of bioethanol in the world. Mainly it is sugar and starch-containing raw materials and cellulose-containing products (waste processing of grain, wood, straw, etc.). Fuel ethanol, in contrast to food, can be produced by shortened distillation, so it contains methanol and fusel oils, as well as gasoline, which reduces the cost of its production and makes it a good alternative to traditional fuel.

The active use of ethanol as a motor fuel for diesels is constrained by the fact that in a number of physical and chemical properties it differs significantly from diesel fuel. The cetane number of ethanol is 5 times lower than that of diesel fuel, which requires special measures to ignite the fuel-air mixture when using alcohol in diesel engines: use of additives, changing the design parameters of the diesel engine (changing the shape of the combustion chamber increasing the compression ratio, the temperature rise of the air charge), the use of glow plugs or spark ignition from glow fuel etc.

The use of alcohols in diesel engines can achieve a significant reduction in the smokiness of exhaust gases. The greater the proportion of alcohol used, the lower the soot content in the exhaust gases. Injection of alcohols into the combustion chamber in the liquid phase by a single nozzle
together with the ignition fuel or using a dual fuel supply system allows to reduce the smokiness by 2 or more times. The injection of alcohols directly into the diesel cylinder by a separate nozzle allows to reduce the smokiness of the exhaust gases as much as possible.

The soot formation during the combustion of alcohols increases with increasing of their molecular mass. Methanol combustion don't forms soot and among combustion products of ethanol, the amount of soot is small.

Ethanol has a high heat of vaporization, so its evaporation in the cylinder leads to a decrease in the temperature in the pre-flame zone cracking, slowing down the chemical processes of the formation of nuclei of carbonaceous particles [1]. There is a hydrogen inhibition of radical chain processes of high temperature cracking, known as the Langmuir effect. Hydrogen as a chemical reagent is able to actively influence the processes of the resulting soot. In the high temperature phase, hydrogen catalyzes the process of accelerated combustion of the soot particle. During the decay of alcohol molecules, the system is not only saturated with hydrogen radicals, but also with hydroxide group radicals ($\text{OH}$), which slow down the processes of dehydrogenation and contribute to the breakage of chains at the stages of formation of soot particles nuclei radicals. It is obvious that the presence of an oxygen atom in the ethyl alcohol molecule restrains the growth of the chain reaction rate of formation of soot nuclei.

Formed during decomposition and combustion of the alcohol radicals of hydrogen and hydroxyl groups and also water molecules and hydrogen increase the rate of gasification of carbon, which leads to the phenomenon of so-called "wet gasification". Analyzing the tendency to soot formation of a fuel in a combustion chamber in a diesel cylinder, it is also necessary to evaluate its physical properties that affect the quality of mixture formation. In other words, the process of mixing has a strong influence on the combustion process and the formation of dispersed carbon. The main parameters that affect the quality of fuel spray in the combustion chamber are surface tension, fuel viscosity, boiling point, heat of evaporation, heat of combustion, cetane number. The main physical properties of fuels are given in table 1. The experience of using alcohols as a fuel in diesel engines and analysis of their physical properties becomes apparent that the cyclic portion of the delay period of ignition of the alcohol increases, more low-boiling fuel evaporates, the mixture becomes more uniform in volume. Decreases the total share of fuel involved in the diffusion combustion, this increases the speed of diffusion. All this together leads to a significant reduction in the of smokiness of diesel engines.

**Table 1.** Properties of diesel fuel and ethanol.

| Fuel properties                                | Diesel fuel | Ethanol  |
|-----------------------------------------------|-------------|----------|
| Density at 20 °C (kg/m^3)                     | 825         | 788      |
| Lower calorific value (kJ/kg)                 | 43.0        | 26.8     |
| Kinematic viscosity at 40 °C (mm^2/s)         | 2.6         | 1.8      |
| Cetane number                                 | 50          | Roughly 8|
| Bulk modulus of elasticity (bar)              | 16,000      | 13,200   |
| Boiling point (°C)                            | 180–360     | 78       |
| Latent heat of evaporation (kJ/kg)            | 250         | 840      |
| Stoichiometric air-fuel ratio                 | 15          | 9.0      |
| Oxygen (% by wt.)                             | 0           | 34.8     |

It should also be borne in mind that ethanol has a lower value of the lower calorific value compared to diesel fuel (26800 and 42500 kJ/kg, respectively), which forces to increase the cyclic fuel supply to preserve the power performance of diesel. The range of ethanol fuel flare has a comparable value compared to diesel fuel. However, the average diameter of the droplets decreases, the flow rate increases, which increases the rate of evaporation of alcohol in the combustion chamber and improves the quality of mixing, ultimately reducing the smokiness of diesel exhaust gases. This uniform distribution of the charge in the combustion chamber is ensured by an increase in the ignition delay period and affects the local temperature characteristics in the areas of soot formation and gasification.
Figure 1 shows the calculated functions of changes in local temperatures in the fuel pyrolysis and soot gasification zones depending on the angle of rotation of the crankshaft. Zero degrees corresponds by the top dead center.

![Graph showing calculated functions of changes in local temperatures](image)

**Figure 1.** Estimated functions of local temperature changes in the diesel cylinder when working on ethanol and diesel fuel.

Such characteristics of temperature fields cause, on the one hand, a decrease in the rate of chain reactions of nucleation of soot particles, on the other hand, the rate of heterogeneous reactions of carbon burning from particle surface in the soot gasification zone decreases. Another characteristic feature of the combustion process of ethanol, as mentioned above, is a significant delay in the heat release in the cylinder. In this case, the heat supply to the working fluid is intense, the combustion process does not stretch in time, there is an additional opportunity to boost the diesel by controlling the angle of advance of fuel injection and the ratio of the portion of ignition fuel and ethanol.

Any suitable environmentally friendly renewable fuel, such as rapeseed oil, which is popular in a number of countries, can be used as the ignition fuel. This solution makes it possible to completely abandon the use of diesel fuel, since most of the work today is aimed at studying the optimal mixed fuel. Mixtures of ethanol and diesel fuel, and mixtures of vegetable oils and diesel fuel are studied [2], [3], [4]. The use of a separate injection system of rapeseed oil and ethanol without the use of diesel fuel leads to a significant decrease in the soot content in the exhaust gases while maintaining the engine performance. Figure 2 shows the characteristics of the maximum pressure in the cylinder and the maximum averaged temperature of the gases in the cylinder, depending on the change in the engine load.

The low maximum gas pressure in the cylinder at low loads causes deterioration of the effective performance of the diesel engine on ethanol and leads to an increase in fuel consumption. This causes additional emission of incomplete combustion products including soot. However, the soot content of the exhaust gases is still less than that of the diesel engine (figure 3). This can be explained by the saturation of the local zones of the combustion chamber with oxygen, which is contained in alcohol molecules. The maximum temperature of the gases in the cylinder is also lower at low loads. With increasing load increases the efficiency and completeness of combustion of ethanol, reduced ignition delay period. At the same time, the maximum combustion pressure and the maximum averaged temperature of the gases in the cylinder increase. As the temperature increases, the rate of soot burning increases, but the excess air coefficient decreases, the mass of fuel in the cylinder increases, the volume of fuel-enriched zones in the combustion chamber increases, hence the concentration of soot in the exhaust gases increases. The increase in the concentration of soot in the exhaust gases when working on diesel fuel is more intense.

At the nominal operating mode diesel engine 2F 10.5/12.0 (frequency of the crankshaft of the
diesel 1800 min\(^1\) and an average effective pressure of 0.588 MPa), ethanol consumption was 5.4 kg/h, rapeseed oil - 1.4 kg/h.

**Figure 2.** Maximum pressure of gases in the cylinder (MPa) and the maximum averaged temperature of gases in the cylinder (K).

**Figure 3.** Exhaust smoke (Bosch unit).

The concentration of soot is reduced 3.8 times. The smokiness of diesel exhaust gases when working on diesel fuel is 5.3 units on the Bosch scale, when working on ethanol and rapeseed oil - 2.2 units on the Bosch scale.

**References**

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