# Bio-fuel ignition delay research

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**Abstract.** The relevance of this study is due to the need to replace petroleum diesel fuel with motor fuels obtained from alternative raw materials. Rapeseed oil and ethyl alcohol are considered as promising alternative fuels. The use of these biofuels as a motor fuel makes it possible to solve the problem of reducing carbon dioxide emissions into the atmosphere and switch to carbon-neutral energy. The possibility of using mixtures of these fuels as motor fuel for a diesel engine is considered. Poor flammability of these fuels in the combustion chamber of a diesel engine was noted. The created installation allowing to carry out experimental studies of the ignition delay period of various fuels for diesel engines in the conditions of the engine stand is described. Four types of fuel were studied at this installation – petroleum diesel fuel, rapeseed oil, an emulsion of rapeseed oil and ethyl alcohol in a ratio of 90:10 and an emulsion of rapeseed oil and ethyl alcohol in a ratio of 70:30. The kinetic constants of ignition of these fuels have been determined. A significant dependence of the duration of the ignition delay period on the type of fuel used was noted.

## 1 Introduction

The main requirements currently imposed on internal combustion engines (ICE) regulate the content of toxic components in exhaust gases – nitrogen oxides, carbon monoxide, unburned hydrocarbons and soot. An effective means of meeting these requirements is the addition of oxygen-containing additives to petroleum diesel fuel, as which vegetable oils, esters of vegetable oils, various esters and alcohols can be used. Among these additives, methanol and ethanol should be distinguished: in methyl alcohol molecules, the mass oxygen content is about 50%, and in ethyl alcohol molecules – about 35 % [1, 2, 3]. The use of methanol as an oxygen-containing additive to diesel fuel is constrained by the toxicity of this alcohol. Therefore, the most promising use for these purposes is ethyl alcohol (ethanol). Ethanol is already widely used in a number of countries (USA, Brazil, etc.) as fuels (or additives to petroleum fuels) in engines with forced ignition. It should be noted, however, that the burning of alcohol fuels, and with better fuel efficiency, is also possible in diesels [4, 5, 6]. At the same time, not only individual biofuels are used, but also their mixtures [7, 8, 9]. At the same

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time, this alcohol has a number of disadvantages that prevent its widespread use as fuels for diesel engines. This is, first of all, its poor self-flammability [10-13]. To assess the flammability of fuels and the dynamics of the subsequent combustion process of fuels in diesel cylinders, various indicators are used: the ignition delay period (IDP) $\tau_i$, the maximum combustion pressure $p_z$, the degree of pressure increase during combustion $\lambda=p_z/p_c$ ($p_c$ is the pressure of the end of compression), the maximum pressure rise rate $(dp/d\varphi)_{\max}$ and the average the rate of pressure increase $(dp/d\varphi)_{\text{mid}}$ during combustion ($p$ and $\varphi$ are the pressure in the cylinder and the angle of rotation of the crankshaft), the dynamic factor of the cycle $\sigma_e=q_{\tau i}/q_c$ ($q_c$ and $q_{\tau i}$ are the cyclic fuel supply and the amount of fuel entering for $\tau_i$) [14]. Among these indicators, the most important are the cetane number and the IDP $\tau_i$, which determine the values of the remaining indicators of the dynamics of the fuel combustion process [15-18]. This is due to an excessively large amount of fuel supplied and prepared for combustion by the time of the start of self-ignition with an increase in the IDP $\tau_i$. Therefore, combustion occurs more rigidly, i.e. with a large maximum pressure rise rate $(dp/dt)_{\max}$ and a large average pressure rise rate $(dp/dt)_{\text{mid}}$ (or estimated by the angle of rotation of the crankshaft – $(dp/d\varphi)_{\max}$ and $(dp/d\varphi)_{\text{mid}}$.

To calculate the duration of the indicator ignition delay period ti, its dependence on the temperature and pressure of the beginning of compression, obtained for reactions with normal kinetics, is often used, where $c$ is a constant multiplier; $p$ is the pressure at the start of fuel injection; $n$ is an indicator of the reaction order; $E$ is the conditional activation energy; $R$ is the gas constant; $T$ is the temperature in the combustion chamber at the start of fuel injection.

$$\tau_i = cp^{-(n-1)}e^{\frac{E}{RT}} \qquad (1)$$

When determining $\tau_i$, it is important to choose the right constant coefficients included in equation (1). However, many studies on the flammability of liquid fuels to determine their kinetic constants were carried out in bombs. In them, the working process (the static state of charge at the time of fuel injection, the constancy of the volume of the combustion chamber, the inability to reproduce several consecutive cycles, etc.) is very different from the working process of diesels. In addition, the published values of the constant coefficients *E, n, c* in various sources [19, 20] very often do not provide information either about the measurement or calculation methods used, or about the conditions under which the experiments were conducted. This circumstance can lead to an error in mathematical calculations and subsequently to contradictory conclusions. Kinetic constants *E, n, c* for rapeseed oil and its mixtures with ethyl alcohol have not been given in the literature so far, which makes it difficult to model the working process of a diesel engine using, in particular, selected unconventional fuels. The purpose of this study is to clarify the values of kinetic ignition constants of various biofuels.

## 2 Research methodology

It is possible to find the kinetic constants E, n, c of fuels for equation (1) by experimentally studying them under various ignition conditions. This problem can be solved by considering the results of three different tests in which the temperatures and pressures of the working fluid change. In particular, a change in the ignition conditions of the fuel in the engine is achieved by changing the moment of injection and (or) the compression ratio. Now we have a system of three equations with three unknown constants:

$$\tau_{i1} = cp_1^{-(n-1)}e^{\frac{E}{RT_1}}$$

$$\tau_{i2} = cp_2^{-(n-1)} e^{\frac{E}{RT_2}}$$

$$\tau_{i3} = cp_3^{-(n-1)} e^{\frac{E}{RT_3}} \quad (2)$$

After logarithm:

$$\ln \tau_{i1} = \ln c - (n-1) p_1 + \frac{E}{RT_1}$$

$$\ln \tau_{i2} = \ln c - (n-1) p_2 + \frac{E}{RT_2}$$

$$\ln \tau_{i3} = \ln c - (n-1) p_3 + \frac{E}{RT_3} \quad (3)$$

As a result of solving a system of three equations with three unknowns, we obtain dependencies for determining the kinetic constants *E, n, c:*

$$n = 1 - \left[ \frac{\left(-\frac{T_2}{T_2 - T_1}\right)\ln \tau_{i2} + \left(\frac{T_1}{T_2 - T_1}\right)\ln \tau_{i1} + \left(\frac{T_3}{T_3 - T_1}\right)\ln \tau_{i3} - \left(\frac{T_1}{T_3 - T_1}\right)\ln \tau_{i1}}{\left(-\frac{T_2}{T_2 - T_1}\right)\ln p_2 + \left(\frac{T_{a1}}{T_2 - T_1}\right)\ln p_1 + \left(\frac{T_3}{T_3 - T_1}\right)\ln p_3 + \left(\frac{T_{a1}}{T_3 - T_1}\right)\ln p_1} \right] \quad (4)$$

$$c = e^{\left[\frac{T_2 \ln \tau_{i2} - T_2 (1-n) \ln p_2 - T_1 \ln \tau_{i1} + T_1 (1-n) \ln p_1}{(T_2 - T_1)}\right]} \quad (5)$$

$$\ln \tau_{i3} = \ln c - (n-1) p_3 + \frac{E}{RT_3} \quad (6)$$

Conducting research under various conditions requires a serious approach to assessing the influencing factors. The ignition delay period in a diesel engine is affected not only by the cetane number of fuel, but also by other factors: for example, inlet conditions, temperature and pressure in the cylinder, operating mode, heat exchange conditions, mixture composition, fuel atomization quality, etc. Therefore, in order to assess the effect of fuel characteristics on the ignition delay period, it is important to conduct studies under comparable conditions with the control of influencing factors and their management.

## 3 Experimental equipment

In carrying out these studies, an IDT-69 type installation developed at the RUDN University was used, designed to assess the flammability of diesel and alternative fuels by the flash matching method, with devices necessary to stabilize external conditions. To improve the accuracy and convenience of measurement, this installation has been upgraded (Figure 1).

The equipment is a stand with a single-cylinder vortex-chamber diesel compartment 43, driven by an electric motor 48 to maintain a constant speed of rotation of the crankshaft and start-up. The operation of the installation is controlled from the control panel 1, which also has control and measuring devices. To maintain the required air temperature at the inlet, a heater 8 of the air entering the cylinder is installed in the collector 7, the flow rate of which is controlled by a flow meter 6. The oil temperature in the crankcase is stabilized by means of a heater 26. The required water temperature in the cooling system is maintained by a heat exchanger 10 installed in the expansion tank 11.

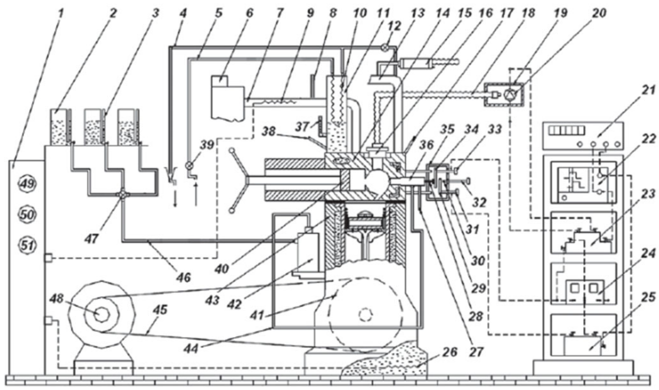

**Fig. 1.** Diagram of the upgraded IDT-69 installation: 1 – control panel; 2 – capacity of the studied fuels; 3 – beaker; 4 and 5 – drain and supply of cooling water; 6 – air flow meter; 7 – intake manifold; 8 – intake air heater; 9, 17, 38 – thermometer; 10 – heat exchanger; 11 – expansion tank; 12, 39 – water tap; 13 – exhaust pipe; 14 – compartment head; 15 – exhaust gas collector (smoke meter); 16 – optical sensor; 18 – light guide; 19 – photo sensor; 20 – photodiode; 21 – frequency meter; 22 – oscilloscope; 23 – amplifier; 24 – power supply; 25 – electric filter; 26 – oil heater; 27 – nozzle fuel drain; 28 – insulator; 29, 34 – nozzle needle movement contacts; 30 and 33 – terminal and screw for adjusting the gap between contacts; 31, 32 – screw; 35 – nozzle needle stroke sensor; 36 – pin nozzle; 37 – compartment cooling system beaker; 40 – adjusting piston; 41 – flywheel compartment; 42 – high–pressure fuel pump (injection pump); 43 – single–cylinder compartment; 44 – high–pressure fuel line; 45 - belt drive; 46 - low-pressure fuel line; 47 - switching valve of the studied fuels; 48 – electric motor drive compartment; 49 – pressure gauge; 50 – rheostat; 51 – thermometer.

For this, running water is used, taken from the water supply. The compression ratio in the installation is changed by moving the adjusting piston 40 in the head 14 of the compartment using a screw pair. As a result, the volume of the vortex combustion chamber changes, which has a cylindrical shape with a connecting channel located tangentially in the vortex chamber and connecting it to the cavity above the piston. A nozzle 36 with a pin sprayer and a contact sensor 35 for monitoring the movement of the sprayer needle is installed in the vortex chamber along the axis of the cylindrical part.

On the cylindrical surface of the vortex chamber in the area of the fuel jet of the nozzle, an optical sensor 16 is installed to control the moment of ignition of the fuel jet. The photodetector of the sensor 19 is removed from the compartment by means of a light guide 18, which allows to stabilize the temperature of the sensor. To be able to analyze exhaust gases, the exhaust system 13 has a selector 15. To determine the ignition delay period at the IDT-69 installation, a system was developed for measuring the time between the start of injection (lifting the spray needle) and the start of ignition of the fuel jet (the appearance of a light signal from a photo sensor). For this purpose, the standard membrane-type sensor has been replaced by an optical sensor consisting of an optical receiver and a photo sensor. The optical receiver is installed in place of the standard membrane sensor and is connected to the photo sensor using a light guide. The proposed method for determining the ignition delay period at the IDT-69 installation made it possible to increase the accuracy of the experiment and the convenience of signal registration processing.

The receiver of the optical sensor uses quartz glass with a low coefficient of expansion, due to which it withstands a high temperature that promotes self-cleaning of its surface from carbon deposits (Figure 2).

The ignition delay period at the IDT-69 installation was determined as follows: the signal from the needle stroke sensor of the nozzle 35 was sent to the first input of the oscilloscope 22 (Figure 1). The moment of ignition of the fuel was recorded by a photodiode 20 located in the optical circuit of the light guide 18 transmitting the light signal. Radiation through the quartz glass 9 of the optical sensor (Figure 2) was transmitted to the photodiode 20 of the photodetector 19 (Figure 1). The electrical signal received in the sensor after amplification in the amplifier 23 was fed to the second input of the oscilloscope 22. The ignition delay period was recorded directly on the oscilloscope screen by the displacement of signals from the sensors of the nozzle needle and photodiode. After debugging the measuring system, the oscilloscope was replaced by the frequency meter Ch3-63/1 21, operating in the pulse duration measurement mode. Such an installation allows for a controlled experiment in which the following factors can be stabilized with a small error: the angle of advance of fuel injection; the cyclic fuel supply; the speed of rotation of the crankshaft; the temperature of the coolant, oil and air intake; the movement of the air charge in the combustion chamber.

The rapid transfer of equipment to work with various test fuels allows us to estimate the duration of the ignition delay period for these fuels and the effect on it of temperature and pressure in the combustion chamber, which can be controlled by changing the compression ratio during the operation of the installation. The study of fuels containing rapeseed oil and ethyl alcohol required the creation of a special mixer (Figure 3), which made it possible to obtain a mixture of rapeseed oil and alcohol without adding an emulsifier, the presence of which could affect the duration of the ignition delay period and distort the result.

The mixer (emulsifying device) mounted on the IDT-69 installation took fuel from the tank 2 (Figure 1) and returned it back. In the process of circulation through the system, the mixture was mixed. The mixer performance was regulated by changing the rotation speed of the electric pump drive. A jet was installed at the outlet of the gear pump to increase the mixing efficiency and eliminate the formation of a vapor-air phase due to the active evaporation of light fractions of ethyl alcohol.

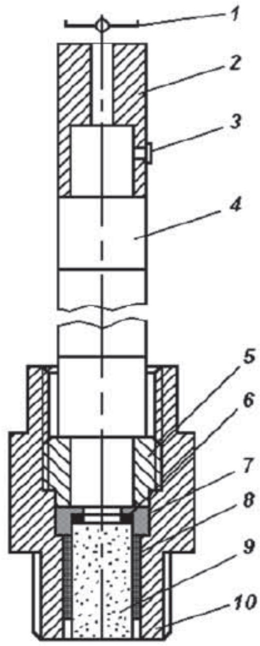


**Fig. 2.** Optical sensor device: 1 – photodiode; 2, 5, 7 – bushing; 3 – screw; 4 – light guide; 6 – gasket; 8 – asbestos seal; 9 – quartz glass; 10 – housing.

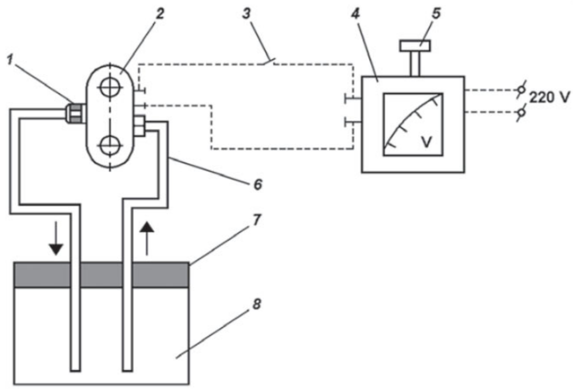


**Fig. 3.** Mixer device: 1 – jet; 2 – gear pump; 3 – switch; 4 – voltage regulator; 5 – adjustment knob; 6 – fuel lines; 7 – plug; 8 – fuel tank.

## 4 Results of experimental and theoretical studies

During the experiment, four fuels were studied: diesel fuel (DF), rapeseed oil (RO), a mixture (emulsion) of rapeseed oil and ethyl alcohol (EA) in a ratio of 90:10, a mixture (emulsion) of rapeseed oil and ethyl alcohol in a ratio of 70:30. Tests of various fuels were carried out at the same coefficient of excess air $\alpha = 2.2$, which allowed to preserve the thermal state of the combustion chamber. Before the start of the tests, the density p and the kinematic viscosity v of the studied fuels were measured at 15 ºC (Table 1).

**Table 1.** Density and kinematic viscosity of fuels at a temperature of 15 ° C.

| Fuel | Density ρ, kg/m³ | Kinematic viscosity v, mm²/s |
|---|---|---|
| DF | 840 | 7.2 |
| RO | 921 | 112.9 |
| Mixture 90% RO и 10% EA | 902 | 59.5 |
| Mixture 70% RO и 30% EA | 890 | 472 |

Studies of the duration of the ignition delay period of various fuels at the upgraded installation according to the described methodology were carried out in two stages. At the first stage, the compression ratio varied and the fuel injection advance angle remained unchanged, at the second stage, the compression ratio remained constant, and the injection advance angle changed. The studies were carried out for the following fuels: DF, RO, a mixture of 90% RO + 10% EA and a mixture of 70% RO + 30% EA (the volume composition of the mixtures is indicated).

The experimental results obtained (Figure 4) for the ignition delay period $\tau_i$ are well approximated by curves monotonically decreasing with an increase in the compression ratio ε. For each fuel, the curve has its own character of change. In the entire studied range of compression ratio, the smallest ignition delay period has DF. For RO having a smaller cetane number, this period increases. The longest ignition delay period was noted for RO and ES mixtures, and the increase in the content of ethyl alcohol in these mixtures increases the ignition delay. The obtained result is in good agreement with the known data on the cetane numbers of individual components. DF has the highest cetane number (45...49), followed by rapeseed oil (35...38) and ethyl alcohol (6...9). At compression degrees $\varepsilon<14$, injection advance angle $\theta = 13°$ before TDC and the use of rapeseed oil and its mixtures with ethyl alcohol, fuel ignition was no longer observed.

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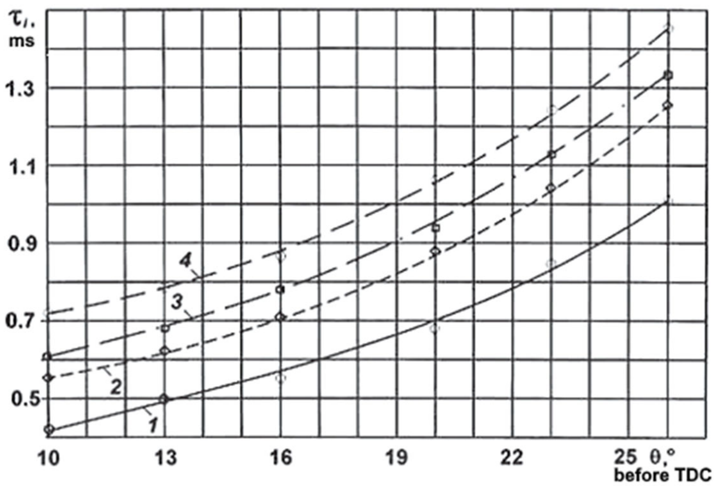


**Fig. 4.** The dependence of the ignition delay period $\tau_i$ on the compression ratio ε at the fuel injection advance angle θ= 13 ° before TDC, obtained at the IDT-69 installation when testing various fuels: 1 – DF; 2 – RO; 3 – mixture of 90% RO and 10% EA; 4 – mixture of 70% RO and 30% EA.

Similar test results of these fuels were obtained when the injection advance angle θ changed from 10 to 26 ° before TDC at a compression ratio ε = 18 (Figure 5). An increase in θ leads to a decrease in the temperature of the working fluid in the combustion chamber at the time of injection, which increases the ignition delay $\tau_i$.

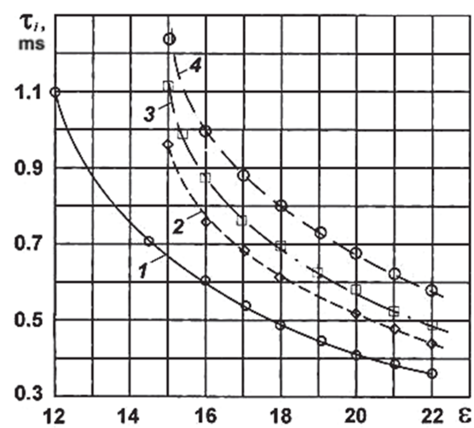


**Fig. 5.** The dependence of the ignition delay period $\tau_i$ on the fuel injection advance angle θ at the compression ratio ε = 18, obtained at the IDT-69 installation when testing various fuels: 1 – DF; 2 – RM; 3 – mixture of 90% RO and 10% EA; 4 – mixture of 70% RO and 30%EA.

To determine the kinetic constants of equation (1), the experimental results obtained were processed taking into account the temperature and pressure in the cylinder at the time of fuel injection. The method of determining the conditions in the engine cylinder was as follows. The pressure in the cylinder corresponding to the beginning of fuel injection was determined directly from the expanded diagram (Figure 6) obtained by indicating compression and expansion in the cylinder of the IDT-69 installation at different degrees of compression ε= 12... 22.

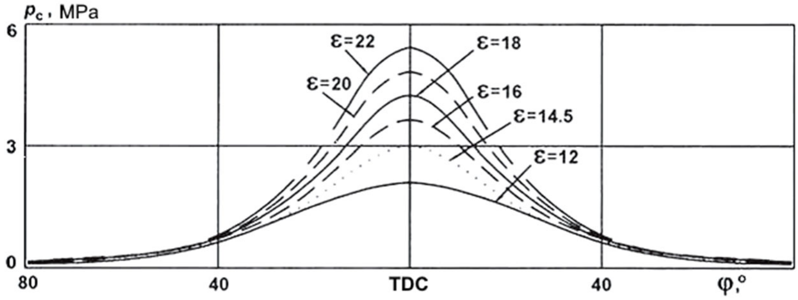


**Fig. 6.** Experimental indicator diagrams of pressure in the combustion chamber during compression-expansion without combustion for various degrees of compression at the rotational speed of the crankshaft n = 900 rpm (φ is the angle of the crankshaft rotation).

Assuming the constancy of the compression polytrope index *k*, the pressure *p* and temperature *T* in the cylinder of the installation at the time of the start of fuel injection can be determined as follows:

$$p = p_a \left( \frac{V_a}{V} \right)^k$$

and

$$T = T_a \left( \frac{V_a}{V} \right)^{(k-1)} \quad (7)$$

$p_a$ is the pressure in the cylinder at the beginning of the compression stroke at the bottom dead center (BDC); $V_a = V_h + V_c$ is the volume of the working fluid above the piston in BDC ($V_h$ is the working volume of the cylinder, the volume of the cylinder; $V_c$ is the volume of the working fluid at the end of the compression stroke; k is the compression polytrope index; $V$ is the volume the working fluid at the time of the start of fuel injection; $T_a$ is the air temperature in BDC.

The current specific volume of the working fluid, taking into account the kinematics of the piston movement in the IDT-69 installation, can be found by the expression:

$$V = \frac{V_h + V_c}{\varepsilon} \left[ 1 + \frac{\varepsilon - 1}{2} \left( \frac{1 + \lambda_{\text{cr}}}{\lambda_{\text{cr}}} - \cos\varphi - \frac{1}{\lambda_{\text{cr}}} \sqrt{1 - \lambda_{\text{cr}}^2 \sin^2 \varphi} \right) \right] \quad (8)$$

$V_c = V_h / (\varepsilon - 1)$ is the volume of the combustion chamber; $\lambda_{cr} = r / l_{cr}$ is the parameter of the connecting rod; $\varphi$ is the current angle of rotation of the engine crankshaft. The calculations assumed: atmospheric pressure p = 0.1034 MPa; air temperature in BDC $T_a$ = 343 K; working volume $V_h$=6.25 ×10-4 $m^3$; cylinder diameter D= 0.085 m; piston stroke $S$=0.115 m; crank radius $r = S / 2$; connecting rod length $l_{cr}$ = 0.266 m.

When processing experimental data, the compression polytrope indicator can be found by the formula:

$$k = \frac{\ln\left( \frac{p_c}{p_a} \right)}{\ln \varepsilon} \quad (9)$$

$p_c$ is the pressure in the cylinder at the end of compression.

According to the described method of processing experimental data of the first series of tests at the injection advance angle θ= 13 °before TDC, kinetic constants *E, n, c* were obtained (Table 2). These kinetic constants obtained during the processing of the test results of the second series of studies are shown in Table 3.

**Table 2.** Values of constants *E, n, c* at a constant injection advance angle θ=13 ° before TDC.

| Fuel | ε | p, MPa | T, K | $\tau_i$, ms | E, MJ/kMole | n | c |
|---|---|---|---|---|---|---|---|
| DF | 12.0 | 1.7 | 593 | 1.099 | 12.41 | 1.51 | 0.118 |
| | 14.5 | 2.3 | 673 | 0.705 | 12.40 | | |
| | 16.0 | 2.6 | 700 | 0.610 | 12.41 | | |
| | 18.0 | 3.1 | 748 | 0.490 | 12.40 | | |
| | 20.0 | 3.5 | 791 | 0.409 | 12.40 | | |
| | 22.0 | 4.0 | 836 | 0.347 | 12.39 | | |
| RO | 16.0 | 2.6 | 700 | 0.777 | 15.08 | 1.33 | 0.080 |
| | 18.0 | 3.1 | 748 | 0.623 | 15.07 | | |
| | 20.0 | 3.5 | 791 | 0.521 | 15.07 | | |
| | 22.0 | 4.0 | 836 | 0.442 | 15.06 | | |
| Mixture 90% RO + 10% EA | 16.0 | 2.6 | 700 | 0.869 | 17.25 | 1.20 | 0.054 |
| | 18.0 | 3.1 | 748 | 0.695 | 17.25 | | |
| | 20.0 | 3.5 | 791 | 0.581 | 17.25 | | |
| | 22.0 | 4.0 | 836 | 0.493 | 17.25 | | |
| Mixture 70% RO + 30% EA | 16.0 | 2.6 | 700 | 0.990 | 19.84 | 0.94 | 0.031 |
| | 18.0 | 3.1 | 748 | 0.801 | 19.83 | | |
| | 20.0 | 3.5 | 791 | 0.678 | 19.84 | | |
| | 22.0 | 4.0 | 836 | 0.582 | 19.83 | | |

**Table 3.** Values of kinetic constants *E, n, c* at constant compression ratio ε= 18.

| Fuel | θ, ° before TDC | p, MPa | T, K | $\tau_i$, ms | E, MJ/kMole | n | c |
|---|---|---|---|---|---|---|---|
| DF | 16 | 2.7 | 724 | 0.559 | 12.40 | 1.51 | 0.118 |
| | 21 | 2.1 | 675 | 0.739 | | | |
| | 26 | 1.6 | 624 | 1.017 | | | |
| RO | 16 | 2.7 | 724 | 0.705 | 15.08 | 1.33 | 0.080 |
| | 21 | 2.1 | 675 | 0.920 | | | |
| | 26 | 1.6 | 624 | 1.255 | | | |
| Mixture 90% RO + 10% EA | 16 | 2.7 | 724 | 0.780 | 17.25 | 1.20 | 0.054 |
| | 21 | 2.1 | 675 | 1.010 | | | |
| | 26 | 1.6 | 624 | 1.372 | | | |
| Mixture 70% RO + 30% EA | 16 | 2.7 | 724 | 0.880 | 19.83 | 0.94 | 0.031 |
| | 21 | 2.1 | 675 | 1.101 | | | |
| | 26 | 1.6 | 624 | 1.449 | | | |

Analysis of the experimental data obtained shows that a decrease in the cetane numbers of the components of the studied fuels leads to an increase in their activation energy. A significant dependence of the ignition delay period on the temperature of the working mixture was noted, which worsens the performance of these fuels for conditions in Russia, where the ambient temperature can vary from -40 to 40 °C. The conditional activation energy for rapeseed oil fuel with a 30% alcohol content is 60% higher than for diesel fuel.

At the same time, with increasing sensitivity to temperature, the sensitivity of fuels to pressure decreases (for a mixture of 70% RO and 30% EA, the reaction order is $n \to 1$). This fuel quality is positive for supercharged engines, in which the cylinder pressure at the end of the compression stroke varies greatly with changes in engine load and speed. Thus, the index of the reaction order n for diesel fuel is 38% higher than that of rapeseed oil fuel with a 30% alcohol content. The constant multiplier c for these fuels differed by 3.8 times.

## 5 Conclusion

The experimental installation based on the IDT-69 has been upgraded, which made it possible to conduct studies of the ignition delay period of various diesel fuels in the conditions of a motor installation.

Four types of fuel were studied: diesel fuel (DF), rapeseed oil (RO), a mixture (emulsion) of rapeseed oil and ethyl alcohol (EA) in a ratio of 90:10, a mixture (emulsion) of rapeseed oil and ethyl alcohol in a ratio of 70:30.

The values of these kinetic constants for rapeseed oil and its mixtures (emulsions) with ethyl alcohol have been obtained, which can be used for computational studies of the working process of a diesel engine when operating on these fuels.

These studies have shown a significant dependence of the duration of the ignition delay period on the type of fuel used. For these fuels, the differences in the values of the activation energy $E$ reach 60%, in the parameters of the reaction order $n$ – 38%, in the values of the constant multiplier $c$ – 3.8 times.

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