

Compressibility of blends of diesel fuel with palm oil

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Abstract. The article presents the results of experimental studies to determine the compressibility of mixtures of diesel fuel with palm oil. To determine the compressibility of fuel mixtures in this work, we used a method based on measuring the speed of sound in the fuel in the injection pipeline. A description of a laboratory setup for measuring the speed of sound propagation in a mixed fuel is given, and the experimental procedure is outlined. The results obtained show that with an increase in the initial compression pressures and the density of fuel mixtures, which depends on the volumetric content of palm oil in them, the speed of sound increases, and the compressibility decreases. Formulas are presented that approximate the experimentally found dependences of compressibility on pressure and the proportion of palm oil in the mixed fuel. The results of the research can be used in modeling the fuel supply process of diesel engines operating on mixtures of diesel fuel and palm oil.

1 Introduction

In recent years, in Russia and around the world, one of the directions for improving the environmental performance of diesel engines and saving motor fuels is their adaptation to work on alternative fuels as a renewable energy resource. It can also help solve the problem of climate change. A variety of alternative fuels for diesel engines are vegetable oils and their mixtures with diesel fuel [1, 2].

The economic potential of renewable energy sources is currently estimated at 20 billion tons of reference fuel per year, which is twice the volume of annual production of all types of organic fuel [3, 4]. This circumstance indicates the way for the development of the energy industry of the future, especially regional and local. Industry, agriculture, transport and other industries have been oriented towards traditional petroleum fuels for a long period of development. However, the inexhaustibility and environmental friendliness of renewable energy sources makes it necessary to consider the possibilities of their use in a new way.

The prospects for the use of alternative fuels (AF) are determined by the following global considerations:

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- these fuels are, as a rule, environmentally friendly, when burned, they provide less emissions that pollute the air and contribute to global warming;
- most AF is produced from inexhaustible, renewable resources and stocks;
- the use of AF allows any state to increase energy independence and security.

The greatest prospects, especially for developing countries of the world, are those alternative types of fuel, the initial basis of raw materials for which are vegetable oils and biogas. As a raw material for motor biodiesel fuel of mass use, vegetable oils have the best prospects [5, 6].

According to literature sources [7, 8], in the total breakdown of costs for the production of biodiesel fuel, 75% of its cost is oilseed raw materials. This is its important advantage. For example, in the Democratic Republic of the Congo, the cost of oilseeds from palm is 0.5–0.55 US dollars per liter, while the average price of 1 liter of diesel fuel in this country is about \$1.5–2. Consequently, the use of motor fuels from the indicated raw materials in its original form or after special chemical processing, as well as in a mixture with diesel fuels, in some cases will be economically much more profitable in countries where palm oil is produced in excess.

A feature of palm oil is the presence in its composition of a sufficiently large amount of oxygen (8–12%). This leads to some decrease in the heat of combustion. Thus, the lower calorific value is 37.1 MJ/kg versus 42–43 MJ/kg for diesel fuels that contain virtually no oxygen. The peculiarities of the physical properties of vegetable oils and fuels based on them (high density and viscosity) are the reason for the increase in their cyclic supply and hourly consumption compared to diesel fuel. An increase in the length of the jet of atomized biofuels is aggravated by their worse self-ignition ability (an increase in the ignition delay period). Another problem is the deterioration of the quality of the mixing process. This is due to the parameters of the physical and technical properties of the oils listed above. The same problems are typical for palm oil as a feedstock for biodiesel. To improve the quality of mixture formation when working on biofuels, it is proposed to use various design changes in the injection system of a diesel engine [9, 10].

Diesel fuel and palm oil are well mixed, which favorably affects the possibility of using such mixtures as fuel for diesel engines. However, it is necessary to take into account the existing differences in the physical properties of mixed and diesel fuels. Palm oil is more viscous and has a higher density. This contributes to an increase in the diameter of the sprayed fuel droplets and an increase in the fuel torch range. This circumstance can lead to an increase in the amount of fuel falling on the walls of the combustion chamber [11].

A lower value of the palm oil compressibility factor may cause changes in the dynamics of the fuel injection process, such as an increase in the actual fuel injection advance angle, an earlier fuel injection, an increase in the maximum injection pressure. All this complicates the processes of mixture formation and fuel combustion.

When calculating the process of supplying fuel, including mixed fuel, it is necessary to take into account its compressibility depending on pressure, density and other parameters. It is impossible to estimate the degree of influence of the content of palm oil in the mixed fuel on the parameters of the fuel supply process (the value of the cyclic supply, pressure and duration of injection, etc.) during the transition of diesel operation from diesel fuel to mixed fuel without assessing the compressibility of palm oil and its mixtures.

In connection with the foregoing, studies of the properties of mixed fuels based on diesel fuel and palm oil, including their compressibility, are very relevant.

2 The purpose and objectives

The aim of this study is to determine the compressibility coefficient of pure diesel fuel, pure palm oil and their mixtures. The following tasks were set during the study:

- preparation of homogeneous stable mixtures of diesel fuel and palm oil;
- obtaining the dependence of the compressibility coefficients of the prepared mixtures on their volumetric compositions and on the initial compression pressures;
- obtaining the equation of the functional dependence of the compressibility coefficients on the composition of the fuel mixture and the initial compression pressures and analyzing the effect of the compositions and density of mixtures on their compressibility coefficients.

The studies were carried out at the Volgograd State Technical University [12].

3 Object and methods of research

As the object of research were used diesel fuel (DF), palm oil (PO) and their mixtures.

3.1 Method for preparing mixtures

Raw PO, obtained by pressing, was purchased in DR Congo from local non-certified manufacturers. DF was purchased in Volgograd at a gas station.

PO and DF mix very well, and to exclude stratification after mixing it is recommended to approximate the viscosity of these two components. To do this, the PO should be heated to 60–70° C in order to decrease its viscosity in relation to the viscosity of DF. The required kinematic viscosity is in the range from 3 cSt to 8–9 cSt. To obtain samples of homogeneous fuel mixtures, PO was mixed with DF for 30 min following the procedure for mixing vegetable oil and diesel fuel in accordance with the procedure for working under laboratory conditions for the manufacture of mixed fuel [GOST R 52808-2007. “Non-traditional technologies. Energy of biowaste. Terms and definitions”, Input. From 27.12.2007. Moskva, Standartinform, 2008. – 9 p.].

Each sample of the prepared fuel mixture was marked with an indication of the amount of PO: 10%, 20%, 30%, 40%, 50%, 60% by volume per 1 liter of the fuel mixture.

3.2 Method for determining the compressibility

In studies, the true compressibility coefficient α_{tru} and the average compressibility coefficient α_{av} is used [13, 14]. The true compressibility coefficient α_{tru} is determined by the relative change in volume dV/V with a change in pressure dP and is calculated as:

$$\alpha_{\text{tru}} = \frac{1}{V} \frac{dV}{dp} \quad (1)$$

where V – volume of fuel; dV – decrease in the volume of fuel with increasing pressure; dp – relative increase in pressure.

The average compressibility coefficient α_{av} determined when the pressure changes from atmospheric to the selected overpressure p :

$$\alpha_{\text{av}} = \frac{dV}{V \cdot p} \quad (2)$$

The coefficient α_{av} characterizes the average compressibility of the fuel in the considered range of pressure changes. As follows from equation (2), α_{av} is determined from the assumption that the compressibility of the fuel obeys Hooke's law.

In the process of fuel supply, the compressibility of the fuel affects the rate of pressure increase in the high pressure line and the amount of cyclic fuel supply. It is important that the coefficient α_{tru} is used in calculations to describe the compressibility at a given

pressure, and the average compressibility coefficient α_{av} is convenient for evaluating the process in a finite interval from any initial pressure p_0 to the current pressure p [14].

The true fuel compressibility coefficient α_{tru} under conditions of pressure and temperature changes in the direct-acting fuel supply system can be determined experimentally. In such a system, the pressure in the pipeline propagates in the form of a wave at the speed of sound a . This speed can be expressed by the following formula [13]:

$$a = \frac{1}{\sqrt{\rho_{in} \left[\alpha_{tru} + \frac{2}{E} \left(\frac{R^2 + r^2}{R^2 - r^2} + \mu \right) \right]}} \quad (3)$$

where a – the pressure wave propagation velocity, m/s;

α_{tru} – true fuel compressibility factor, Pa^{-1} ;

E – modulus of elasticity of the material from which the pipeline is made, MPa;

R and r – outer and inner radii of the pipeline, m;

μ – Poisson's ratio;

ρ_{in} – the density of the fuel at a given initial pressure, kg/m^3 .

When deriving (3), two assumptions were made:

1) the speed of the fluid is small compared to the speed of sound and therefore is not taken into account;

2) the compressibility coefficient is considered independent of pressure, i.e. fluid compression obeys Hooke's law.

To determine the density ρ_{in} , we use the expression:

$$\rho_{in} = \rho_0 (1 + \alpha_{av} p_{in}) \quad (4)$$

where p_0 – fuel density under normal conditions, kg/m^3 ;

p_{in} – given initial pressure, Pa.

Under normal conditions in pure DF without PO additives $a = 1250\text{--}1450$ m/s.

For each type of fuel mixture, the average compressibility coefficient α_{av} was determined by the expression:

$$\alpha_{av} = \frac{\alpha_0 + \alpha_{30}}{2} \quad (5)$$

where α_0 – compressibility coefficient under normal conditions;

α_{30} – compressibility coefficient at an initial pressure of 30 MPa.

Substituting in equation (3) instead of ρ_{in} its expression, according to equation (4), we get:

$$a = \frac{1}{\sqrt{\rho_0 (1 + \alpha_{av} p_{in}) \left[\alpha_{tru} + \frac{2}{E} \left(\frac{R^2 + r^2}{R^2 - r^2} + \mu \right) \right]}} \quad (6)$$

Since the density of liquids weakly depends on pressure, in (6) the difference between α_{av} and α_{tru} can be neglected. Then, solving (6) with respect to α_{tru} , we obtain:

$$\alpha_{tru} = -\frac{1 + p_{in}k}{2p_{in}} + \sqrt{\left(\frac{1 + p_{in}k}{2p_{in}} \right)^2 + \frac{1}{a^2 \rho_0 p_{in}} - \frac{k}{p_{in}}} \quad (7)$$

where k is the Rothrock correction:

$$k = \frac{2}{E} \left(\frac{R^2 + r^2}{R^2 - r^2} + \mu \right).$$

The compressibility coefficient increases with an increase in temperature, and decreases with an increase in pressure. The value of the fuel compressibility coefficient is influenced by the nature of the compression process, the amount of air contained in the fuel and a number of other factors, which leads to different results even when measuring the compressibility coefficient of the same fuel sample [14].

When conducting experimental studies, the following goals were set:

- determination of the speed of sound in the fuel line for PO and its mixtures with DF;
- determination of the dependence of the compressibility coefficient of the mixed fuel on the volume ratio of PO and DF in it;
- determination of the dependence of the compressibility coefficient of the PM and mixed fuel on the value of the compression pressure.

At the same time, the following tasks were solved:

- creation of an experimental setup for determining the velocity of a pressure wave in a high-pressure pipeline;
- development of a methodology for conducting experiments and processing their results.

The compressibility coefficients of PM and its mixtures with DF were calculated according to the method of prof. I. V. Astakhov on the basis of the measured values of the velocity of propagation of a pressure pulse along a long pipeline - the local velocity of sound [13].

We used an experimental stand (Figure 1), created on the basis of a stand for injectors adjusting KI-3333.

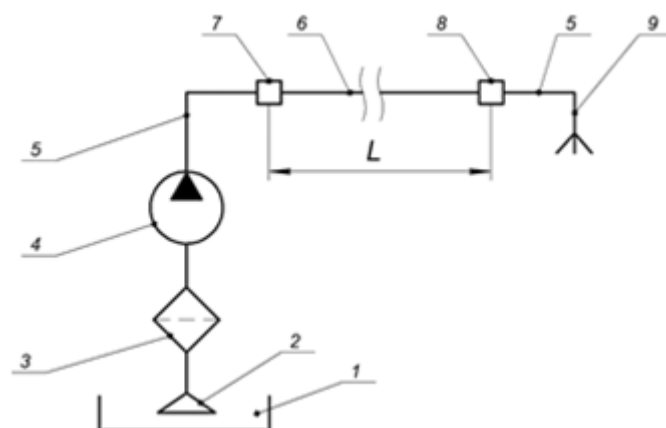


Fig. 1. Hydraulic scheme of the experimental setup: 1 - container with fuel; 2 - fuel intake; 3 - filter; 4 - discharge section of the high pressure fuel pump; 5 - connecting pipelines; 6 - discharge pipeline; 7 - inlet pressure sensor; 8 - outlet pressure sensor; 9 - injector.

In the installation, a regular manual single-plunger high-pressure pump of the with a cut-off edge and a discharge valve was used. The length of the connecting pipelines 5 is minimized as much as possible in order to reduce the volume of the system. An FD-22 injector was used as the end volume, which was adjusted to different injection start pressures.

At the inlet and outlet of the discharge pipeline 6, pressure sensors 7 and 8 of the BD type, model PD-R, manufactured by BD (India) are installed with the following technical characteristics:

- measuring range: 0...60 MPa;
- error: 0.5% of the measurement limit;
- output signal: 4...20 μ A;
- power supply: DC 10...30 V;
- temperature of the measured medium: from -40°C to $+150^{\circ}\text{C}$.

The signal from the sensors was registered and recorded using an analog-digital converter Z230 produced by Zetlab, operating in two-channel mode, using PowerGraph software.

The experimental procedure was as follows. The injector needle spring was tightened to a certain injection start pressure, then fuel was pumped into the pipeline using a high-pressure manual pump. After raising the pressure to values close to the opening pressure of the injector needle, the pump lever was sharply pressed to inject fuel through the injector. The pressure waves in the pipeline that arose at that moment were registered by sensors and an oscilloscope and recorded in the computer's memory. After that, the injector opening pressure increased and the experiments were repeated. For the accuracy of the results, at each injector opening pressure, the experiments were repeated 3 times, with at least 25 fuel injections performed.

The oscillogram of the signals of the input and output pressure sensors is shown in Figure 2. Changing the characteristics of the fuel pressure at the inlet and outlet of the pipeline allows you to set the speed of the pressure wave through it. Areas with a sharp increase in pressure were used for the analysis. At the same time, it is noticeable that the pressure pulse at the output sensor lags relative to the input pressure pulse. This delay Δt characterizes the time interval required for the pressure wave to pass through the pipeline. The pressure wave velocity a was determined from the moments of occurrence of pressure pulses in the inlet and outlet sections of the pipeline according to the formula:

$$a = \frac{L}{\Delta t} \quad (8)$$

where L is the actual distance between the sensors, m.

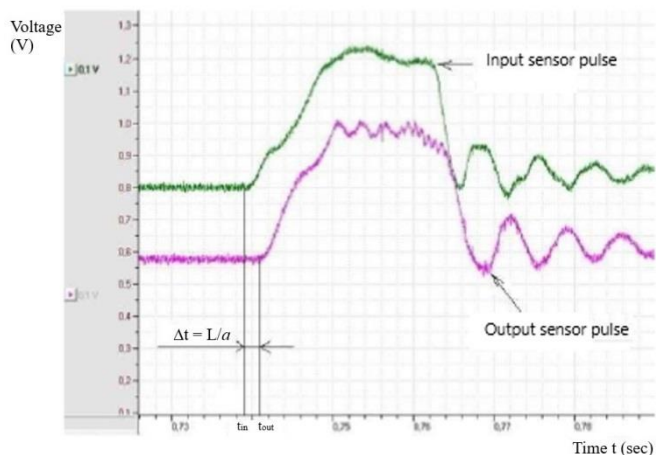


Fig. 2. Oscillogram of pressure pulse propagation in the pipeline.

The experimental conditions are as follows: ambient temperature $t_0 = 24\text{ }^{\circ}\text{C}$, ambient pressure $p_0 = 100\text{ kPa}$, mixture temperature $t = 50\text{ }^{\circ}\text{C}$. Nozzle injection start pressure $P_f = 100, 200, 300, 400\text{ bar}$. The fuel pressures at the beginning of compression p_{in} were determined from the oscillograms of the input and output sensor signals at the moments of a sharp increase in pressure before injection (see Figure 2). The different levels of input and output sensor signals are explained by their different scales.

4 Results and discussion

On Figure 3a and 3b show, respectively, the dependences of the pressure pulse propagation velocity a , which is equal to the speed of sound in the fuel, and the true compressibility coefficient α_{tru} on the initial pressure p_{in} for various fuel mixture compositions, including pure DF and PO. In further discussion, we will consider only the true compressibility coefficient α_{tru} and denote it without an index, i.e., α .

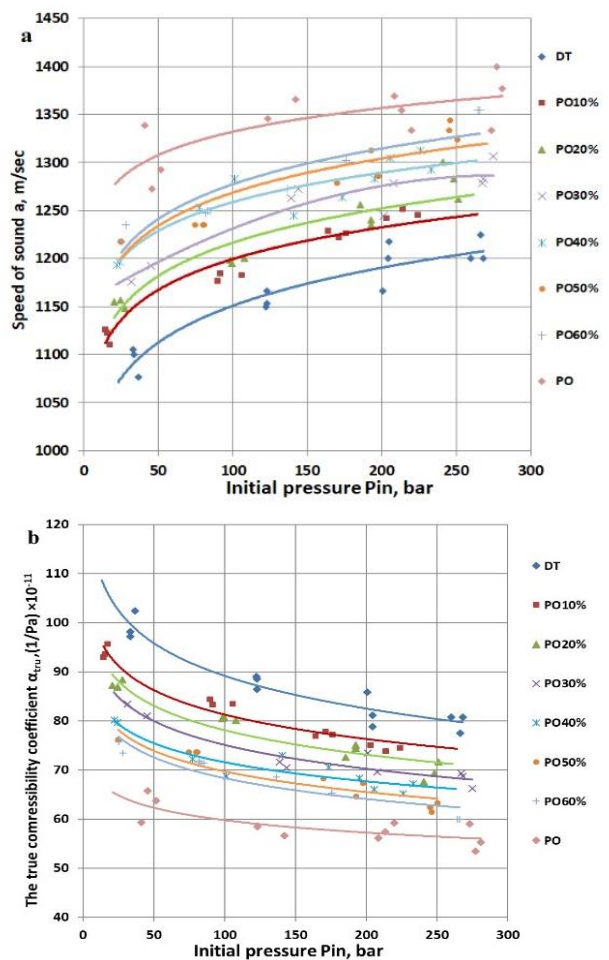


Fig. 3. (a) Dependences of the speed of sound propagation a on the initial pressure p_{in} with different mixture compositions; (b) Dependences of the compressibility coefficient α_{tru} on the initial pressure p_{in} with different mixture compositions.

The obtained dependences for mixed fuels correspond to the nature of similar dependences of the compressibility coefficient for a number of heavy fuels [14]. Let us describe the general form of the approximating polynomials for the values of the compressibility coefficient by the equation of the 2nd degree:

$$y = a_2 x^2 + a_1 x + a_0 \quad (9)$$

With a constant composition of the mixture g_m , the compressibility coefficient α will depend on the initial pressure p_{in} and equation (9) will have the form:

$$\alpha = a_2 p_{in}^2 + a_1 p_{in} + a_0 \quad (10)$$

As a result of processing the experimental data presented in Fig. 3b, the following approximating polynomials are obtained for various compositions of mixed fuel:

$$\left. \begin{aligned} \alpha &= 4.618 \cdot 10^{-15} P_H^2 - 2.371 \cdot 10^{-12} P_H + 1.097 \cdot 10^{-9} \\ \alpha &= 3.445 \cdot 10^{-15} P_H^2 - 1.770 \cdot 10^{-12} P_H + 9.658 \cdot 10^{-10} \\ \alpha &= 3.455 \cdot 10^{-15} P_H^2 - 1.774 \cdot 10^{-12} P_H + 9.344 \cdot 10^{-10} \\ \alpha &= 3.361 \cdot 10^{-15} P_H^2 - 1.726 \cdot 10^{-12} P_H + 9.003 \cdot 10^{-10} \\ \alpha &= 2.696 \cdot 10^{-15} P_H^2 - 1.384 \cdot 10^{-12} P_H + 8.353 \cdot 10^{-10} \\ \alpha &= 2.912 \cdot 10^{-15} P_H^2 - 1.495 \cdot 10^{-12} P_H + 8.264 \cdot 10^{-10} \\ \alpha &= 2.937 \cdot 10^{-15} P_H^2 - 1.508 \cdot 10^{-12} P_H + 8.137 \cdot 10^{-10} \\ \alpha &= 1.755 \cdot 10^{-15} P_H^2 - 9.011 \cdot 10^{-13} P_H + 6.756 \cdot 10^{-10} \end{aligned} \right\} \quad (11)$$

An analysis of the obtained approximations shows that the coefficients of polynomial (10) depend on the composition of the mixed fuel g_m , i.e.:

$$\alpha = f_2(g_m) p_{in}^2 + f_1(g_m) p_{in} + f_0(g_m) \quad (12)$$

where $f_0(g_m)$, $f_1(g_m)$, $f_2(g_m)$ – the dependences, respectively, of the coefficients a_0 , a_1 and a_2 of the approximating polynomial (10) on the composition of the fuel mixture g_m .

For the functions $f(g_m)$, in turn, polynomials approximating them were obtained, depending on the fraction of PO g_m in the mixed fuel. The resulting approximations of the dependence of the coefficients of polynomials (10) on the value of g_m are shown in Figure 4, which also shows approximating expressions of the 2nd degree.

Substituting the approximating expressions $f(g_m)$ into equation (12), we obtain a formula for calculating the value of the compressibility coefficient α depending on the initial pressure p_{in} and the composition of the fuel mixture g_m :

$$\begin{aligned} \alpha &= (4.228 \cdot 10^{-15} - 3.389 \cdot 10^{-17} g_m + 9.802 \cdot 10^{-20} g_m^2) p_{in}^2 + \\ &+ (-2.164 \cdot 10^{-12} + 1.664 \cdot 10^{-14} g_m - 4.372 \cdot 10^{-17} g_m^2) p_{in} + \\ &+ (1.059 \cdot 10^{-9} - 5.824 \cdot 10^{-12} g_m + 2.066 \cdot 10^{-14} g_m^2) \end{aligned} \quad (13)$$

This expression can be used in modeling fuel supply processes to determine the compressibility coefficient α for different compositions gm of PO and DF fuel mixtures and for different values of the initial pressure P_{in} with an error of less than 5%.

5 Conclusion

As a result of the experiments carried out according to the developed method, the values of sound velocities in the fuel were obtained during the passage of pressure pulses in the injection pipeline for diesel fuel, palm oil and their mixtures.

The compressibility coefficients were determined from the obtained values of sound velocities. The values of the obtained sound velocities and compressibility coefficients for the fuels and mixtures under consideration generally coincide with the data obtained earlier [13, 14] for hydrocarbon fuels of similar densities. An equation for the functional dependence of the compressibility coefficient on mixture compositions and initial fuel injection pressures is obtained.

Thus, the data obtained can be used to model the process of fuel supply in diesel engines when they are adapted to work on mixtures of diesel fuel and palm oil.

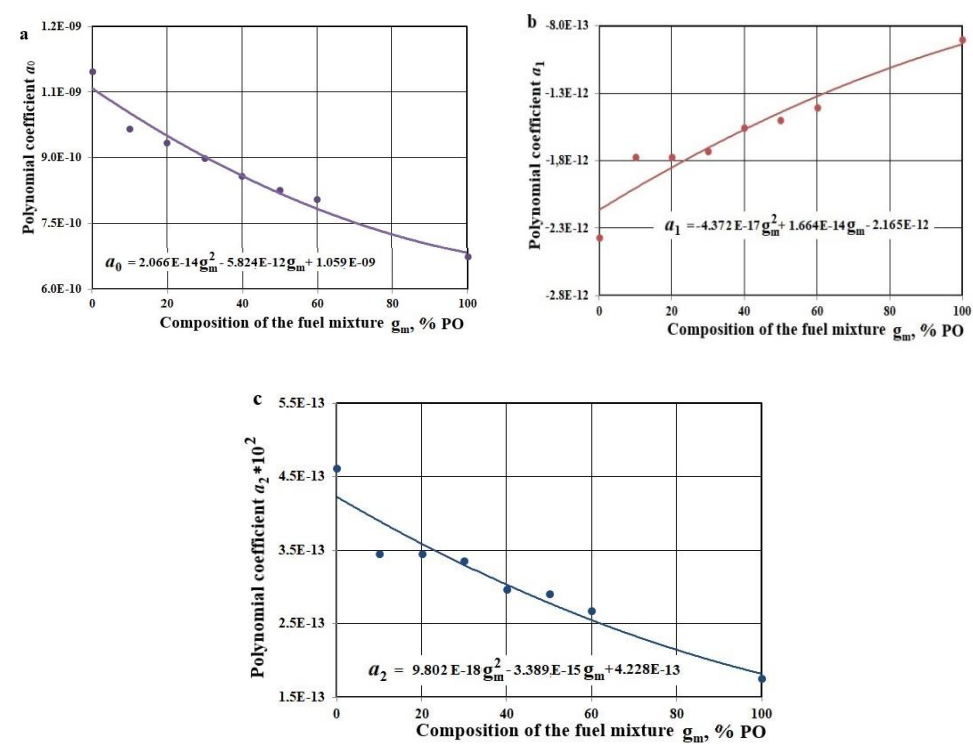


Fig. 4. Dependence of the polynomial coefficients (10) on the composition of the fuel mixture g_m : (a) - coefficient a_0 ; (b) - coefficient a_1 ; (c) - coefficient a_2 .

References

1. M. Dabi, U. K. Saha, Journal of the Energy Institute **92**(6), 1710-1726 (2019)

2. A. Murugesan, C. Umarani, R. Subramanian, N. Nedunchezian, *Renewable and Sustainable Energy Reviews* **13-3**, 653-662 (2009)
3. N. D. Avarskij, V. V. Taran, Zh. E. Sokolova., E.A. Silko, *Economy of Agricultural and Processing Enterprises* **7**, 55-63 (2017)
4. Production volume of palm oil worldwide from 2012/13 to 2022/23 (Statista, 2023)
<https://www.statista.com/statistics/613471/palm-oil-production-volume-worldwide/#:~:text=Palm%20oil%3A%20global%20production%20volume%202012%2F13%2D2022%2F23&text=The%20global%20production%20of%20palm,metric%20tons%20in%202020%2F21>.
5. J. Januan, N.Ellis, *Renew Sustain Energy Rev.* **14**, 1312-1320 (2010)
6. P. Gumpon, A. Teerawat. Palm oil as a fuel for agricultural diesel engines: Comparative testing against diesel oil (2003)
https://www.journeytoforever.org/biodiesel_SVO-palm.html
7. M. Hossain, M. A. Kalam, H. H. Masjuki, A. Alam, M. M. Rashed, H. K. Imdadul, M. Islam, *Energy Conversion and Management* **105**, 617-629 (2015) DOI: 10.1016/j.enconman.2015.08.020
8. V. A. Markov, A. I. Gayvoronsky, L.V. Sin, N.A. Ivashchenko, *The work of diesel engines on non -traditional fuels* (Legion-Autodata, Moscow, 2008)
9. M. G. Shatrov, V. I. Mal'chuk, A. U. Dunin, et al., *Automotive Industry* **5**, 9-11 (2012)
10. A. V. Bizhaev, *Agricultural Machines and Technologies* **6**, 41-46 (2017)
11. S. Salim, S. H. I. Abdel, V. V. Bernatsky, et al., *Izvestia MGTU MAMI* **2(40)**, 14-19 (2019) DOI: 10.31992/2074-0530-2019-40-2-14-19.
12. E. T Kadiata., V. M. Slavutskiy, A. V. Kurapin, et al., *Bulletin of the Irkutsk State Technical University* **22-10**, 178–188 (2018) DOI: 10.21285/1814-3520-2018-10-178-188.
13. I. V. Astakhov, *Energomashinostroyeniye* **9**, 8–11 (1960)
14. L. V. Grehov, I. I. Gabitov, A. V. Negovora, *Design, calculation and technical services fuel supply systems of diesel engines* (Legion-Avtodata, Moscow, 2013)