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DEVELOPMENT OF THE METHODOLOGY AND SUBSTANTIATION OF FUEL SUPPLY PARAMETERS IN THE TRANSITION TO BIOFUEL

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Abstract

Changing the nature of the workflow of the diesel engine, increasing its technical and economic performance when converting to work on alternative fuels is pronounced when using mixed fuels. The differences between these properties of the components of different in both composition and ratio of fuels affect primarily the process of fuel supply, fuel spraying, evaporation and mixture formation.

The article proposed a technique for reconfiguring the fuel supply system to operate on biofuel. Also, the parameters of the systems operation when using the F-22 injector were substantiated, at which the performance of the power system will be achieved closest to the nominal values.

Keywords: *fuel, modeling, nozzle, torch, fuel injection, biodiesel, mixture.*

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1. Introduction

The diesel engine power supply system performs a number of functions, namely: preserving the fuel supply, purification of water and impurities, dispensing fuel, supplying and ensuring the necessary dynamic qualities of the engine, especially in transition modes.

It is quite obvious that when using biofuel and its mixtures, the mechanical system does not meet such requirements. The decrease in injection pressure and the quality of atomization leads to the subsidence of large drops of fuel and a decrease in the efficiency of the engine. To solve the problems associated with the use of biofuels, it is advisable to develop a dual-circuit adaptive diesel power system that works depending on the loading and speed modes of the engine (Demirbas A., 2008).

The advanced system will not degrade the operation of the diesel engine and provide basic power and torque.

One of the most effective methods of studying the processes of fuel supply and mixture formation in diesels is the simulation of these processes using various mathematical models. It should be taken into account that the improvement of mixing process in diesels with semi-separable and inseparable combustion chambers (CC) is performed mainly by increasing the fuel injection pressure and the number of spray nozzle openings. Important indicators of the injection and spraying processes affecting the quality of the mixture formation are the length L and the width B of the fuel jet spray, the angle of the cone of the opening β jet, the spray dispersion (Burlaka, S.A., *et al.*, 2019).

Optimization of these parameters should be carried out for a wide range of speed and load modes of auto tractor diesels. The determination of these indicators by experimental methods is time-consuming and not always possible due to the large number of factors affecting the mixture formation. When improving these processes, it is necessary to determine the dynamics of the development of fuel jets for which various calculation methods are proposed. One of the first works is the publication of F. Sass in 1929, in which the range (length) of the fuel jet L is proposed to be determined by the logarithmic dependence on time t:

$$`L = (l / k) \cdot In \cdot (1 + k \cdot Co \cdot t), \qquad (1)$$

where Co is the initial rate of fuel leakage from the spray hole; $k = 3 \cdot \rho v \cdot cx / (4 \cdot \rho t \cdot dp)$ coefficient; ρt - density of air and fuel; cx is a dimensionless coefficient of aerodynamic resistance; dp is the diameter of the hole. A large number of studies are devoted to models in which the range of the fuel jet is defined as a static [4]: (Marchenko A.P. *et al.*, 2004):

$$L = A \cdot B^{x} \cdot C^{y} \cdot D^{z}, \tag{2}$$

where B, C, D are the criteria values; A, x, y, z are coefficients.

The calculation of the range of the fuel jet is usually performed for average values of the parameters during fuel supply.

The advantage of these models is the simplicity of the computational studies and the visual impact of the factors on the range of the fuel jet, but the degree of influence of the same factors on different models may differ by 2 or more times (Marchenko A.P. et al., 2004). Among the first domestic models of the fuel jet development can be noted the model of I. Astakhov, built on the example of the dynamic equilibrium friction of forces acting under the jet front:

$$- m_T \cdot dC_f / dt = 2 \cdot \rho_B \cdot S \cdot c_x \cdot C_f^{1,5}, \tag{3}$$

where m_T - is the mass of fuel; C_f - velocity of the jet front; S - is its area. This model, as well as the models proposed by other scientists, was designed to account for the unsteady fuel supply of the nozzle.

But they differ in the complexity of mathematical relations and require a large amount of computer resources. Therefore, techniques based on the analysis of experimental data are widely used. They can be divided into two groups:

- the calculation of the advance of the jet front in terms of average parameters of fuel supply;
- the calculation of the range of the fuel jet for the promotion of individual portions, which have their characteristics depending on the law of fuel supply.

The range of the fuel jet according to the criterion dependence proposed by Lyshevsky A. looks like:

$$L = A \cdot d_p \cdot We^{a} \cdot Lp^{b} \cdot E^{m} / \rho^{n}, \tag{4}$$

where We, Lp, E – Weber, Laplace and Euler criteria.

The coefficients A, a, b, m, n of equation (2,4) are chosen as a function of the relative air density ρ specified in the form of

$$\rho = \rho_B / \rho_T , \tag{5}$$

The range ofthe fuel jet by a portion of the aerodynamic model proposed by Trusova V., Rabikina L. (MADI), is determined by the maximum range of the portion, which looks like:

$$L_i = 1n \cdot [(HC_{0i}(t - t_i) + 1)] / H, \tag{6}$$

where C_{oi} - initial flow rate of *i*-portion [м/с]; t - injection start time [с]; t_i- the fuel jet departure time of *i*-portion [с]; $H = c_x \cdot \rho / (2 \cdot \xi \cdot d_p^{2})$-settlement complex; $c_x = 0,4$ – dimensionless drag coefficient of *i*-portion of drip-air mixture.

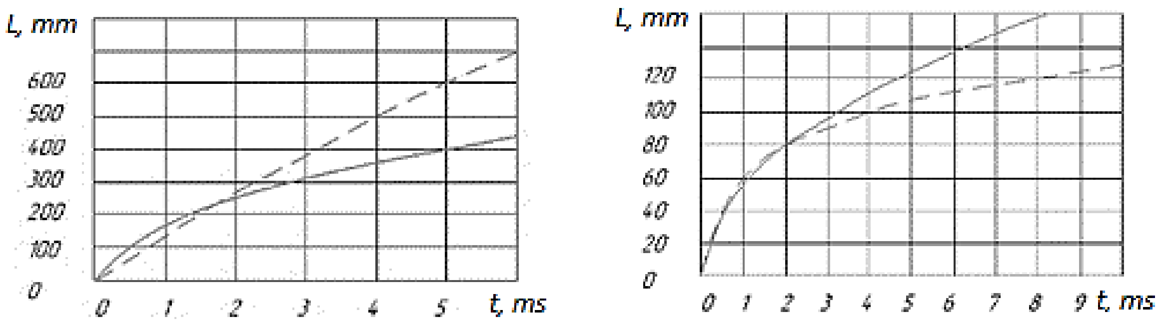


Fig. 1. Estimated values of the fuel jet length L: solid line - by the method of A. Lishevsky; intermittent - MADI technique [28] , a - p_{inj}= 26 MPa , p= 0,1 MPa, d = 0,54mm, б – p_{inj}= 26 MPa, p = 1,1 МПа, d = 0,23 mm.

A possible reason for the divergence of the MADI calculation results may be:

- variability of coefficient tscx i ξ, which have been accepted as permanent;

-movement of fuel portions throughout the jet development area has been assumed to be independent of each other, which does not allow to take into account the effect of energy feeding the jet front;

- selection of coefficients has been carried out according to the law of supply, usually has a domed appearance (rather than rectangular) (Burlak S.A., 2020).

The criterion model in the form of a static polynomial cannot satisfy the modern requirements, as it is obtained for the case of fixed fuel consumption and requires a complete generalization of the law of supply, which limits its application especially for stepped and multiple laws. Therefore, there is a need to create a model of the fuel jet development that takes into account the true law of fuel supply and adequately reflects the impact by observing the main factors: process time t; air density ρ_v; the diameter of the spray hole d_p; the injection pressure g_f. This method of calculation was created on the basis of the momentum conservation law (Gunko I.V., Burlak S.A., Yelenich A.P., 2018) but it is necessary to more accurately determine what effect biofuel and its mixtures will have on diesel characteristics.

2. Materials and Methods

The following approach to this problem is used in the development of the technique. The jet created by the nozzle is non-stationary, heterogeneous, and consists of unequal droplets of finely-sprayed fuel and its vapors, which move in the air and interact with each other and the air. The initial energy of the fuel coming out of the spray hole is eventually dissipated in the environment. Therefore, the velocity of the jet decreases as it develops (Grabar I.G. *et al.*, 2011; Anisimov V.F. et al., 2008). Finding a solution to the problem in the form of the movement of individual droplets, taking into account their interaction with the surrounding air, vapors of fuel, as well as with each other, is a difficult task that is not easy to solve because of the complexity of the initial conditions and the inability to calculate a large number of droplets of different sizes. To simplify the task, the following assumptions have been made:

1. The structure of the fuel jet is considered as two zones of the front and the body of the jet, which differ in the nature of interaction both inside the jet and with the surrounding air;
2. Consideration should not be given to a single drop, but to a group of drops and vapors of fuel formed by spraying a portion of fuel;
3. A portion of the fuel supplied moves in a jet according to its law, interacting with the environment and not with previously submitted portions;
4. When the fuel front portion is reached, energy is exchanged between them on the basis of the momentum storage law;
5. The jet front interacts with the air resulting in an energy exchange based on the law of momentum storage;
6. The exchange of trajectories is considered only in the straight-line direction of motion of the fuel jet.

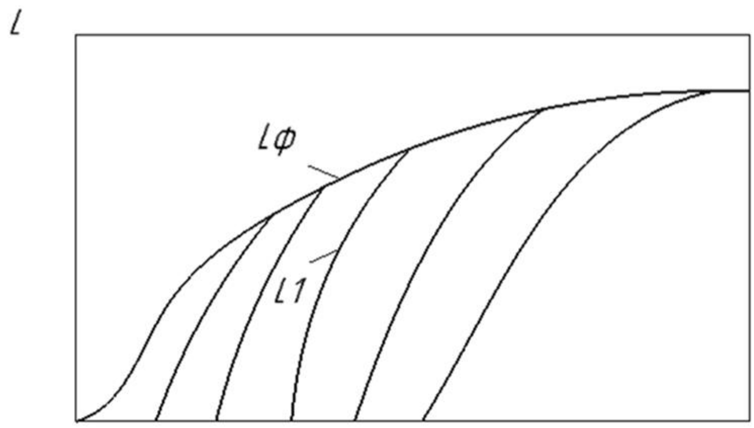


Fig. 2. Characterization of the jet length L

Similar scientific results on the jet spreading have been obtained by M. Kukhareva and I.Gershman. It is shown in Fig. 2, where the laws of displacement of individual portions (characteristics Lf) moving inside the jet at a velocity above the front velocity (characteristic L1) are considered. The jet structure is a heterogeneous mixture of liquid fuel and gas. A portion of fuel is considered to be a group of droplets that have the same characteristics and obey the same laws. In this case, the forces acting on the portion, applied to the center of mass of the group of droplets forming the portion. This approach can significantly reduce the number of equations describing the motion of the jet (Semenov V.G. *et al.*, 2015, Borysiuk D. *et al.*, 2021). One portion of fuel movement is independent of other portions. This assumption also simplifies the solution of the problem. The nature of the interaction of portions in the jet has not yet experimentally determined. The model of such interaction is absent. To simplify the dependencies obtained, a fraction of the energy lost that is proportional to the jet velocity should be taken. This assumption is acceptable, because the main time the flow of jets occurs at Reynolds numbers Re<2500, where the resistance of the jet motion in the air flow is related to the velocity linear dependence. The use of momentum conservation law is for fuel portions and jet front. This position follows from the model, when the portion of the fuel overtaking the front brakes to the speed of its movement, transmitting the impulse of the front accelerates it (Rutkevych V. *et al.*, 2022)

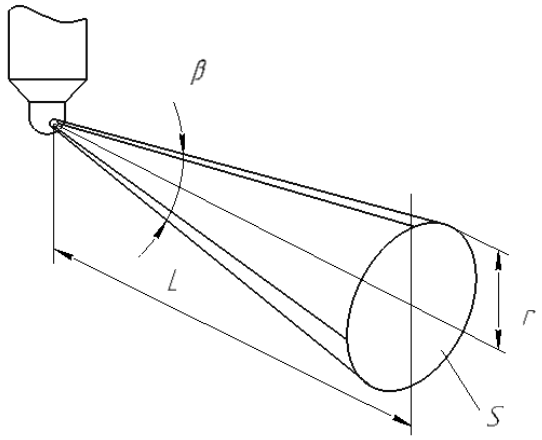


Fig. 3. Geometric characteristics of the fuel jet

The amount of air involved in the interaction with the front depends on its effective surface area. The magnitude of this area S can be estimated by the length L and the cone angle β of the jet (Fig. 3) in the form S = π • t • r2, where r = L • tg (β / 2). The magnitude of the jet opening angle depends on many factors: the density of the medium into which the fuel is injected, the physical properties of the fuel, the geometric parameters of the atomizer, the characteristics of the fuel flow, etc. (Rutkevych V. *et al.,* 2021). The analysis of the experimental data shows that the distribution of fuel in the cross section of the jet is well described by the normal law of Gaussian distribution, according to which the density of distribution is determined by the expression (Burlaka, S.A., *et al.*, 2021):

$$\varphi(x) = (1 /\sqrt{2}\pi\, \sigma^2)\ exp[(-0{,}5\ (x - \varepsilon)^2 / \sigma^2, \qquad (7)$$

The distribution of the fuel in the cross section of the jet is estimated by the density of irrigation q_T, ie the amount of fuel per unit of irrigated surface (Barabash V.M. *et al.*, 2018, Malakov O.I., *et al.*, 2019). For the variable *x* the distance from the axis of the jet to the study area is usually chosen, which in the formulation of the problem, describes the radius with the same irrigation density.

Thus, when the irrigation density on the axis of the jet q_0 we obtain the relative density of irrigation:

$$q_T/\ q_0 = exp(-0{,}5\cdot z^2/\sigma^2). \qquad (8)$$

When considering a jet with a constant opening angle *β*, the irrigation area at a certain distance depends on *β*. Thus, we assume that the angle *β* and the varianceσ2 are related parameters. The law of change in the density of irrigation obtained by the capture of fuel at a distance of 50 mm at different points in time is shown in Fig. 5.

Therefore, at a constant fuel flow density, the irrigation density over time, *d*t can be represented as:

$$q_m = A_q \cdot C_T, \tag{9}$$

where A_q- constant coefficient. The force action of a stream with a mass flow rate $G_T = \rho_T d\ S\ C_m$ on the elementary platform *dS* can be expressed by the dependence:

$$dF = G_m \cdot C_m, \tag{10}$$

Given the density of the fuel flow, the force affecting the elemental site *dS* can be expressed as:

$$dF = \rho_{mn} \cdot dS \cdot C_m^2 = A_F \cdot C_T^2, \tag{11}$$

where A_F - constant coefficient. After converting expression (11) through their rogation density with q_m, instead of velocity *Cm*, weobtain:

$$d = (A_F / A_q^2)\ q_T^2 = f(q_m^2), \tag{12}$$

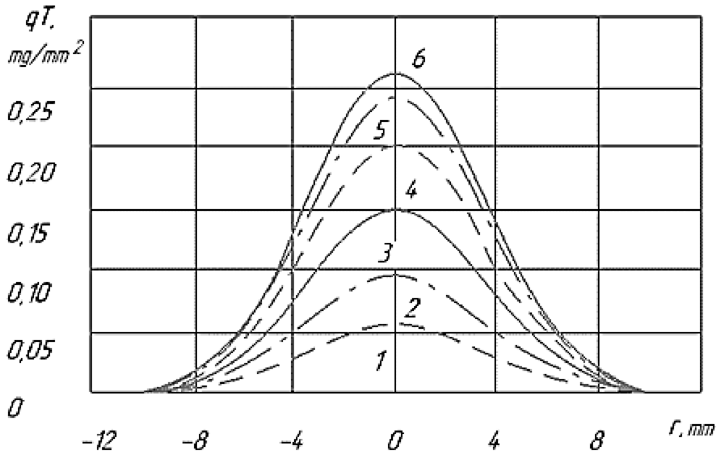


Fig. 4. Changing the dispersion of spraying q_T along the radius of the jet r at a distance of L = 50 mm from a spray hole with a diameter d = 0.25 mm at injection pressure r_{vp} = 1.85 MPa and cycle feed g_{ts} = 8 mg at different points in time τ from the beginning filing: 1-τ = 1,026; 2-1,282; 3-1,538; 4-1,795; 5- 2.05; 6-2,30.

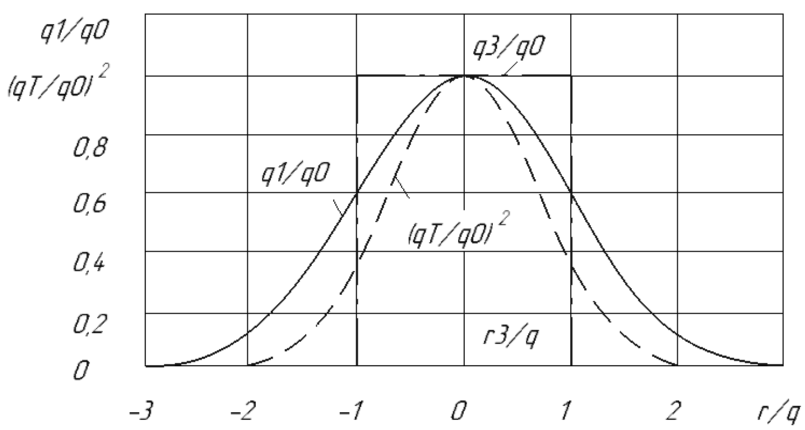


Fig. 5. Characteristic of the change of irrigation density q*T*, square of irrigation density q*T*2 and equivalent density q_e related to axial density q_o.

To find ther adius of the effective crosssection, we compare these jets with a chother. At the same time it is sufficient to compare with each other the integral cross sections of the characteristics q_m^2. For a jet with a normal distribution law, the change in the square of the relative irrigation density is described by the dependence:

$$(q_T / q_o)^2 = exp(-r^2 / \sigma^2), \quad (13)$$

The total value of Q_B (integral characteristic of the relative density of irrigation) in cylindrical coordinates is expressed as a double integral of angle ψ and radius r:

$$Q_n = \int_0^{2\pi} \int_0^{\infty} e^{(-r^2/\sigma^2)} r \cdot dr \cdot d\psi \quad (14)$$

Introducing the new variable x = (r / σ)2, after the transformation we get:

$$Q_n = 0{,}5 \int_0^{2\pi} \int_0^{\infty} e^{(-x)} d\, x\, d\psi \quad (15)$$

After integration within the established limits we have:

$$Q_B = \pi \cdot \sigma^2 \quad (16)$$

Table 1. The results of the computational studies on the effective jet opening angle

Value	(14)		(3)		(21)	(18)	
L, mm	150	250	203	304	50	35	50
r, mm	11,7	21,6	9,7	20,5	2,7	1,2	1,4
tg(β/2)	0,078	0,086	0,048	0,067	0,054	0,034	0,028
B, grad	8,9	9,8	7,7	6,2	6,2	3,9	3,2
$d_{p,}$mm	0,38	0,38	0,635	0,25	0,25	0,32	0,32
$P_{пр,}$MPa	1,8	1,8	1,4	1,85	1,85	1,2	1,2

$Q_n = 0{,}5 \int_0^{2\pi} \int_0^{\infty} e^{(-x)} d\, x\, d\psi$The total value of Q_{np} from the effective intersection of radius r_e with constant irrigation density will be:

$$Q_{BA} = \pi \cdot r_e^{\cdot 2} (q_e / q_o)^2 = \pi \cdot r_e^2, \quad (17)$$

Since $Q_B = Q_{BZ}$, the equivalent radius is equal to the mean square deviation: $r = \sqrt{\sigma^2}$r, ie, the effective cross-sectional area is limited by the radius equal to the mean square deviation of the jet droplets from its axis. The relative density of irrigation at a distance of equivalent radius $r_a = \sigma$will be equal to:

$$q_m / q_0 = exp(-0{,}5 \cdot r_e^2 / \sigma^2) = exp(-0{,}5) = 0{,}6065... = 0{,}607. \quad (18)$$

The characteristic density of irrigation (Fig. 6) is determined by the equivalent radius of the jet r_e in the considered cross section of the jet. The cross sections of r_e form a cone with an effective opening angle of the jet β_e. The radius of the equivalent cross section r_e at a distance L from the spray hole is related to the angle β_e by the dependence (Fig. 7):

$$tg(\beta_e / 2) = r_a / L_ф, \quad (19)$$

The values of β_e obtained in a number of studies vary in the range from 3.2 to 9.8 ° and make up about half of the angle of openness of the jet β (Table 2) observed in the photo and video recording. The accepted assumptions allow to create a model of development of a jet in the following form.

The initial conditions are determined by the density of the medium into which the fuel is injected, the flow rate and the rate of discharge, the initial value of which is C_o. It is determined by the equation:

$$C_0=\varphi\sqrt{(2/\rho_T)(P_{inj}-P_{rp})}, \quad (20)$$

where φ – speed coefficient (for Re> 10000 value φ = 1). The mass of the fuel portion Δmi is determined by the density ρ_T, the volume flow rate through the spray hole Q_i, and the leakage time Δt_i:

$$\Delta m_i = \rho_m \cdot Q_i \cdot \Delta t_i. \quad (21)$$

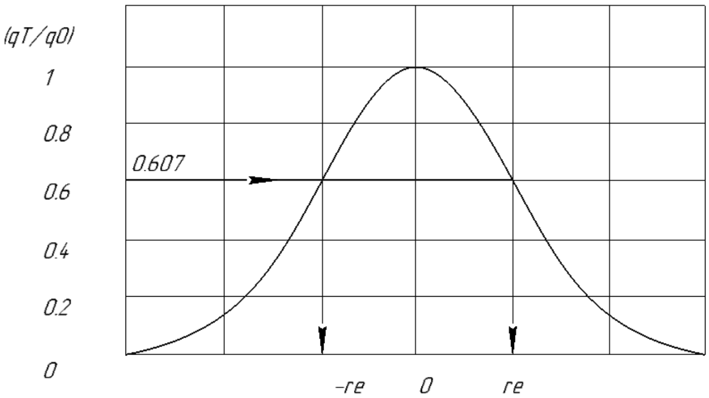


Fig. 6. The scheme for determining the effective value of the jet radius by known irrigation density

Table 2 The values of the parameters k_1, γ_E and the factors ρ,Re affecting them

Experiment number	The pressure of the environment RPR, MPa	Spray pressure, PP, MPa	Diameter of spray hole dr, mm	Coefficient of energy losses k1, m-1	Effective jet opening angle, grad.	The relative density of the medium	Reynold's number Re
1	0,1	26	0,54	2,8	3,8	0,00142	16046
2	0,35	26	0,54	3,4	4,8	0,00496	16046
3	0,6	26	0,54	3,8	6,0	0,00850	16046
4	0,85	26	0,54	4,2	7,2	0,01205	16046
5	1,1	26	0,54	4,5	8,5	0,01559	16046
6	1,45	26	0,54	5,0	10,4	0,02055	16046
7	1,7	26	0,54	5,4	11,6	0,02410	16046
8	1,95	26	0,54	5,7	12,6	0,02764	16046
9	1,1	9,3	0,54	4,7	10,2	0,01559	9597
10	1,1	14,1	0,54	4,7	10,0	0,01559	11817
11	1,1	18	0,54	4,6	9,6	0,01559	13351
12	1,1	30,4	0,54	4,5	8,2	0,01559	17351
13	1,1	41,5	0,54	4,5	7,8	0,01559	20273
14	1,1	26	0,23	4,7	10,6	0,01559	6835
15	1,1	26	0,38	4,5	9,0	0,01559	11292
16	1,1	26	0,70	4,5	8,0	0,01559	20801
17	1,1	26	0,82	4,4	6,8	0,01559	24367
18	1,1	26	1,04	4,4	6,4	0,01559	30904

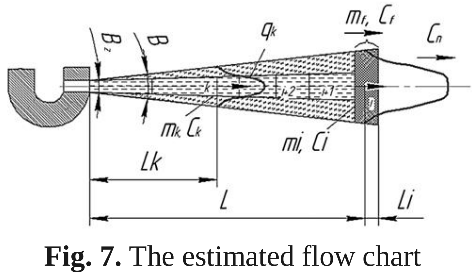
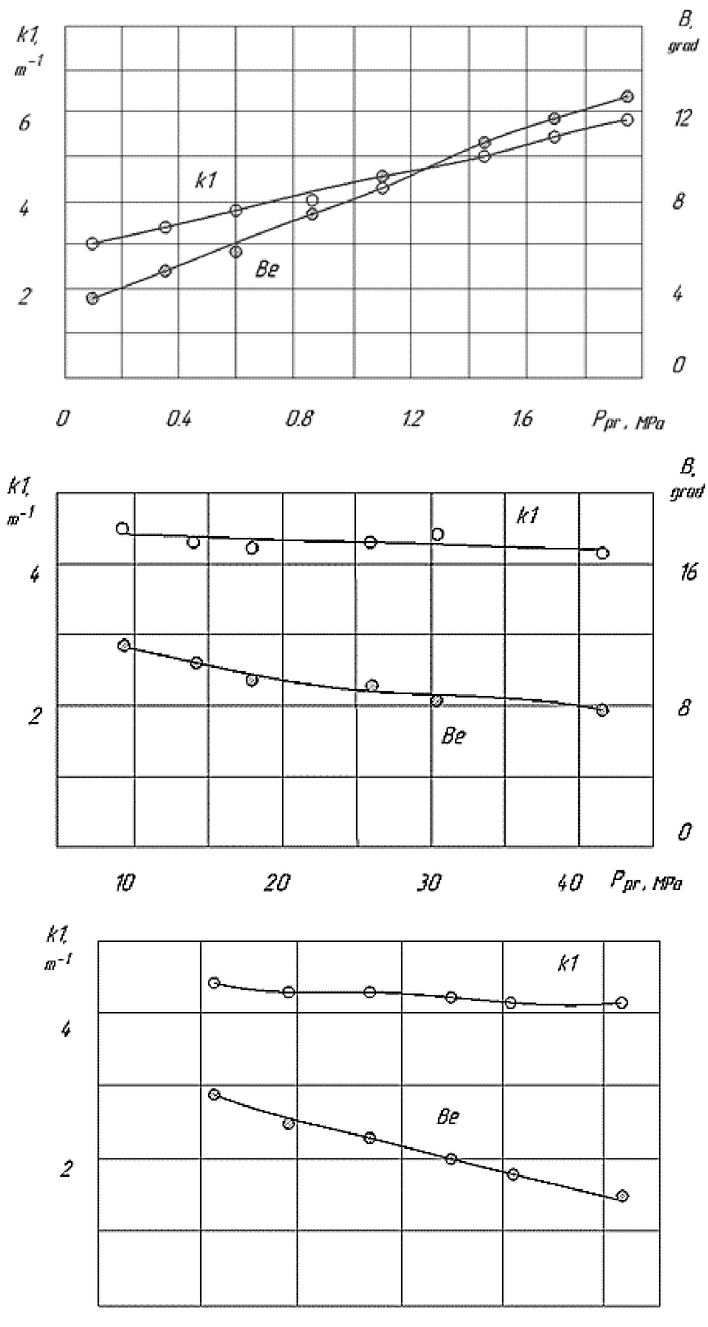


Fig. 7. The estimated flow chart

Integrating the velocity of the portion, we get the law of its movement L until the portion reaches the jet front:

$$L_i = \int_0^t C_i dt = \int_0^t [C_0 / (1 + k_u \cdot t \cdot C_0)] dt = \frac{1}{k_u} ln(1 + k_u \cdot t \cdot C_0), \quad (22)$$

The exchange of energy between the front, the fuel portion and the air is described by the momentum conservation law in the direction of the jet spread (Fig. 8).



(a

(b

(c

Fig. 8. Dependences of the coefficient k_1 and the angle β_e on the counter pressure p_{pr}(a) and the spray pressure p_p (b) of the spray hole diameter d_p (c)

If the calculated span of the second portion exceeds the advance of the front, or equal to it, then the change in front velocity is considered taking into account the second portion. If the second portion does not catch up with the front, then changing its velocity is considered only by its interaction with the air.

The effective opening angle of the jet is determined by the portions that have reached the front. The calculation is made in the specified time range.

For the experiment, we use mineral diesel fuel and biofuel at ambient temperature t=20^{0}C. The research were carried out on the KI-22203 test bench using an FD-22 diesel injector (Fig. 9). The fuel injection angle was determined at different fuel pressures on the injector and the same artificially limited torch range L (Fig. 3). The factory settings of the FD-22 injector were taken as the reference indicator, at which β = 13...15 grad.

Thus, it was assumed that the stable operation of a biofuel engine can be ensured under the condition of maximum similarity of the spray cone when using diesel fuel and biofuel. Considering that the parameter L is determined by the design features of the combustion chamber (L=const=92mm), the only parameter that affects the shape of the spray cone is the angle β, which depends on the physicochemical parameters of the fuel. Therefore, the main task when converting an engine to biofuel is the selection and adjustment of the fuel equipment and its components for operating modes that would ultimately allow the angle β to approach the nominal value β = 13...15 grad, leveling the influence of physical and mechanical properties.

Considering the geometric parameters of the fuel injection stream, we determine the theoretical injection angle β by the formula (see Fig. 3).

$$\beta = arctg\frac{r}{L},\ grad \tag{23}$$

where r is the radius of the jet, mm; L – distance from the nozzle of the hole in the spray surface, mm.

The experimental equipment for the research of fuel supply of the ND-22-6B4 high-pressure pump is presented in Fig. 10.

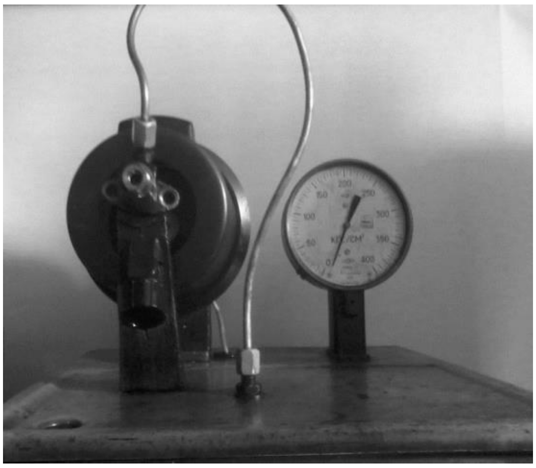


Fig. 9. The measurement of the fuel injection angle at the KI-22203 booth (L=92 mm)

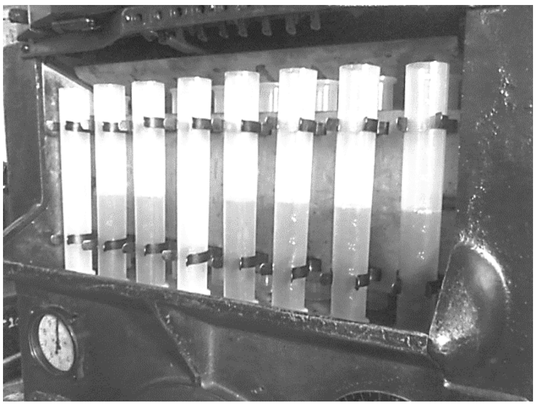


Fig. 10. The measurement of the cycle biofuels supply at the KI-921-M booth

3. Results

The fuel injection angle was determined at different fuel pressures and the same torch range artificially limited. The data of calculations of the fuel injection angle are given in table 3.

Table 3. The results of experimental evaluation of the geometric similarity of the torch depending on the settings of the fuel equipment at L = const = 92 mm, t = 20 ^{0}C

№	P, MPa	Diesel fuel		Biodiesel fuel		Relative deviation β
		r, mm	β, grad	r, mm	β, grad	%
1	10	21,5	13,115	17,4	10,7	19,06977
2	15	24,5	14,895	18	11,03	26,53061
3	17	25,75	15,589	18,12	11,14	29,63107
4	20	27,02	16,330	22,12	13,49	18,13472

As can be seen from Table. 3, the minimum deviation, and hence the maximum geometric similarity of the biofuel injection jet compared to the use of DF is 18.13%, and can be supplied when setting the pump to a value of P=20.0 MPa. In this case, according to the technical characteristics of the SD-22 injector, the recommended value is 17.0-17.5 MPa. At a given value, the optimal shape of the flame torch during fuel combustion is ensured and stable operation of the engine is ensured.

Moreover, as the researchers note (Grabar I.G. et al., 2011; Anisimov V.F. et al., 2008), an increase in the pressure value by more than 10% (in this experiment, an increase of 14.3%) can lead to a violation of the engine power supply, excessive fuel consumption and, as a result, a decrease in engine efficiency. In view of the foregoing, there is a need to implement fuel cycling control, the objective function of which is to level the effect of pressure increase and minimize the difference in the cyclic fuel rate when operating on biofuel compared to diesel fuel.

A graphic representation of the experimental performance of the fuel supply of the ND-22-6B4 pump using biofuels (diagram - 1) and diesel fuel (diagram - 2) is shown in Fig. 11.

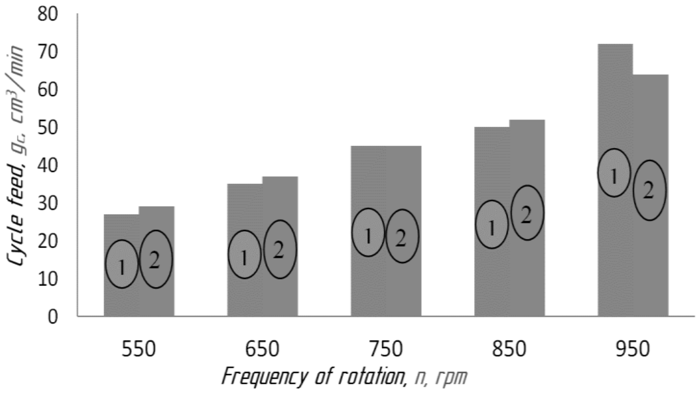


Fig. 12. A graphic representation of the dependence of the fuel supply on the speed of the cam shaft

To adapt the diesel engine to work on biofuels and its mixtures, provided that the nominal performance of the mineral diesel fuel is maintained, a number of operational and experimental measures should be carried out: adjust the fuel equipment to increase the cycle fuel supply (up to 12%); to increase the fuel injection angle (based on experimental studies); calculate the excess air factor for different engine operating modes using biofuels.

Due to the excellent physico-chemical properties of biofuels, its cycle supply rate is reduced within 6.5-7% at n = 550-650 rpm.

The irregularity of the fuel cycle also depends on the physicochemical properties of the fuel and the operation of the plunger pairs. The fuel injection angle is determined for conditions t=20^{0}C and P0=0,1MPa directly depends on the viscosity and density. In real-world conditions, a cylindrical blend of reducing the injection angle of biofuels can increase the torch range. Maintaining the performance of fuel equipment under operational conditions within the limits specified by the manufacturer may result in fuel savings of 2.8% to 12.4%.

4. Conclusions

So, in order to adapt the diesel engine to work on biofuel and its mixtures while maintaining the nominal performance on mineral diesel fuel, it is necessary to carry out a number of operational and experimental measures: the fuel equipment is overcooled to increase the cyclic fuel supply (up to 12%); Based on experimental studies, increase the fuel injection advance angle (12.0) and calculate the excess air coefficient for various engine operating modes using biofuel.

Under equal engine operating conditions L=const=92 mm, t = 20 ^{0}C, the injection angle decreased by 29%. To ensure high technical and economic performance of the engine when running on biofuel, it is necessary to adjust the fuel equipment in order to level the influence of the disagreement between the physical and mechanical properties of diesel fuel and biofuel on the fuel supply parameters. Thus, it was found that the closest approximation to the nominal values of the fuel supply can be achieved at a pressure of 17.0 MPa and a high-pressure fuel pump speed of n=750 rpm. For such conditions, there will be no deviation.

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