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RATIONALE FOR THE PARAMETERS OF EQUIPMENT FOR PRODUCTION AND USE OF BIODIESEL IN AGRICULTURAL PRODUCTION

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Запропоновано технічні рішення, які дозволяють отримувати якісне дизельне біопаливо за рахунок забезпечення перемішування шарів емульсії із використанням циркуляційних змішувачів-розділювачів. Встановлено параметри установки для виробництва дизельного біопалива. Запропоновано використання дизельного біопалива в тракторних двигунах із двоступеневої системою підігріву. Застосування змішувачів дозволяє отримувати дизельне біопаливо за спрощеною технологією в агровиробництві. Застосування системи підігріву розширює температурний діапазон використання чистого дизельного біопалива та зменшує його витрату

Ключові слова: дизельне біопаливо, переетерифікація, змішувач, машинно-тракторний агрегат, система підігріву

Предложены технические решения, которые позволяют получать качественное дизельное биотопливо за счет обеспечения перемешивания слоев эмульсии с использованием циркуляционных смесителей-разделителей. Установлены параметры установки для производства дизельного биотоплива. Предложено использование дизельного биотоплива в тракторных двигателях с двухступенчатой системой подогрева. Применение смесителей позволяет получать дизельное биотопливо по упрощенной технологии в агропроизводстве. Применение системы подогрева расширяет температурный диапазон использования чистого дизельного биотоплива и уменьшает его расход

Ключевые слова: дизельное биотопливо, переэтерификация, смеситель, машинно-тракторный агрегат, система подогрева

1. Introduction

One of the factors increasing the energy efficiency of agricultural production and reducing carbon dioxide emissions is the use of fuel of own production, in particular, liquid biodiesel [1, 2].

For biodiesel production, transesterification process is used [3]. For rapid and complete reaction, methanol and alkaline catalyst are used in the process of transesterification [4–6]. After the transesterification reaction, separation of a glycerol phase and a phase containing fatty acid methyl esters occurs. After adding a methanol-catalyst solution in oil, the biphasic medium, which is unsuitable for the transesterification reaction is formed in the reactor. So, constant stirring is required for emulsification and reaction initiation [4, 5]. A contact interphase surface is formed, which increases the reaction rate. However, excessive stirring leads to the destruction of the contact surface, which prevents complete methanolysis reaction and requires significant energy consumption [4, 5, 7]. Reduction of energy consumption and maximization of the methanolysis reaction completeness are important for biodiesel production at facilities of agricultural enterprises [4, 5].

The biodiesel produced in reactors is similar to diesel, but has a higher kinematic viscosity, cloud point and pour point, lower calorific value [4, 7]. Therefore, the use of biodiesel leads to engine performance deterioration [8] and efficiency reduction of machine-tractor units.

Therefore, the development of energy-efficient equipment and appropriate technologies is important for biodiesel production and more efficient use of biodiesel-driven machine-tractor units at facilities of agricultural enterprises.

2. Literature review and problem statement

The transesterification reaction or methanolysis of oils with alkaline catalysts such as NaOH or KOH are most commonly used in biodiesel production [7]. Biofuel is produced at a temperature of 20–70 °C using catalysts in an amount between 0.3 % and 1.5 % by the weight of oil triglycerides [6]. Rational parameters of the transesterification process correspond to a temperature of about 40 °C, 6:1 methanol-to-oil molar ratio, catalyst concentration of 1 %, stirring intensity of 1.8 W/l, duration of up to 40 min [4, 9].

It is found that the efficiency of the biodiesel formation reaction depends on hydrodynamic conditions [10] and requires determining the key reactor-separator parameters and finding optimum stirring techniques. There are known methods of emulsion stirring in small-capacity reactors using mechanical stirrers [11, 12], fixed «static» hydraulic mixers [13]. The use of conventional [14] and rotating [15] fermentation reactors is also of interest. It follows from the research that the emulsion stirring process is characterized by efficient stirring and energy consumption.

The proposed biodiesel production technologies involve additional washing [16] and purification [17], making it difficult to obtain diesel fuel at facilities of agricultural enterprises.

Much research on the impact of biodiesel on the performance of internal combustion engines is conducted. For example, in [18] the engine load effect on the exhaust gas composition has been evaluated. The studies of the fuel impact on the engine power, specific fuel consumption and exhaust opacity are also carried out [19]. The analyzed studies indicate that biodiesel is consumed by 12...15 % more than conventional diesel. Also, there is little research on improving the performance properties of motor and tractor engines operated by agrarian enterprises.

The analysis leads to the conclusion that available and future equipment for biodiesel production does not fully provide the process efficiency in agricultural production. Moreover, there is insufficient research on the biodiesel impact on performance parameters of machine-tractor units in agricultural production to ensure their efficient operation.

3. The goal and objectives of the research

The goal of the research is to increase the energy efficiency of biodiesel by improving technical means for its production and use.

To achieve the goal, following objectives were formulated:

– to improve the mathematical model of energy-efficient emulsion stirring in circulation mixers-separators (hereinafter mixers);

– to determine the key parameters of mixers;

– to justify the technology of biodiesel production using circulation mixers-separators;

– to determine the patterns of influence of the biodiesel properties on engine performance of machine-tractor units and to develop a fuel heating system;

– to carry out experimental verification of the machine-tractor unit, equipped with a diesel heating system.

4. Materials and methods of the research on the parameters of equipment for production and use of biodiesel

An experimental setup consisting of a circulating reactor for vegetable oil transesterification, hydraulic unit (Fig. 1) and measuring equipment (Fig. 2) (Hitachi-3-G3JX-A4075-EF frequency inverter (Japan), DMK-30 power consumption analyzer (Italy), UT-372 tachometer (China), Acer I3 laptop (China) was designed for the research of energy efficiency of mixers.

Fig. 1. The circulation mixer-separator for vegetable oil transesterification

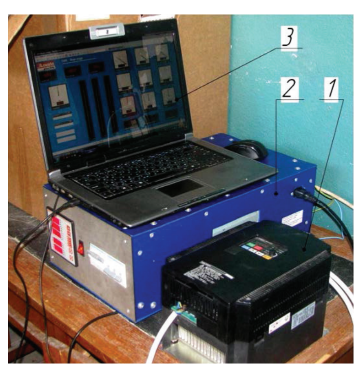

Fig. 2. Measuring equipment: 1 — frequency inverter; 2 — digital power consumption meter; 3 — laptop with special software installed

For the tests, rapeseed oil in an amount of 150 liters, pumped by the hydraulic unit to the mixer to be transesterified was used. The emulsion was stirred at a temperature of up to 40 °C in the composition of rapeseed oil and methanol at a ratio of 6:1.

When testing the biodiesel-driven machine-tractor unit, an experimental two-stage fuel heating system for tractor engines (Fig. 3), installed on the Kyi-14102 tractor (Ukraine) was used.

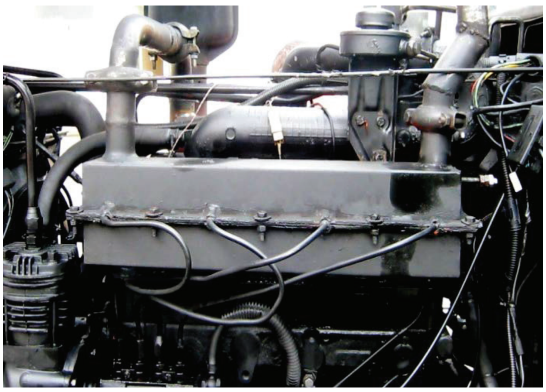

Fig. 3. Heat exchanger of the high-pressure line of the two-stage biodiesel heating system

Biodiesel produced with the proposed mixer was used in the experimental research of the machine-tractor unit.

5. The research results on the parameters of equipment for production and use of biodiesel

For the process of esterification of vegetable oils, circulating mixing by repeated circulation pumping of liquid is proposed. Injectors are installed on the top of the mixer (Fig. 4). The emulsion passage through injectors creates turbulent flow and provides uniform layer-by-layer emulsion stirring.

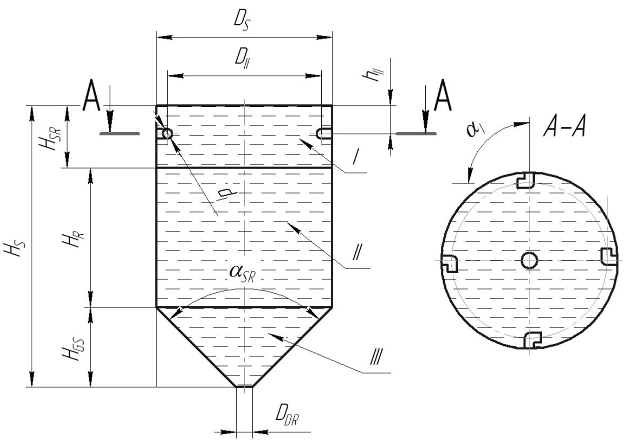

Fig. 4. A block diagram of the mixer: I — stirring region; II — reaction region; III — glycerol settling region; H_S — separator height, m; H_{SR} — stirring region height, m; H_R — reaction region height, m; H_{GS} — glycerol settling region height, m; D_S — separator functional diameter, m; D_{II} — injector installation diameter, m; d_i — injector nozzle diameter, m; h_{II} — injector installation height, m; D_{DR} — glycerol drain hole diameter, m; α_{SR} — settling region taper rate, rad; α_i — injector installation angle, rad.

The emulsion is pumped out from the mixer bottom, the mixed emulsion layer is lowered. Turbulence decreases, higher reaction completeness is achieved.

For the mixer, the emulsion flow rate in the jet section at a distance l_X from the injector can be determined by the following expression:

$$Q_X = \frac{\pi\mu\xi_j k_i d_i}{4}\left(l_X - d_i\right)\sqrt{\frac{2P_i}{\rho_O}}, \qquad (1)$$

where Q_X is the emulsion flow rate in the jet section at a distance l_X from the injector, m^3/s; k_i is the resistance coefficient of the liquid flowing from the injector; l_X is the distance from the injector nozzle to the considered jet section, m; d_i is the injector nozzle diameter, m; μ is the injector nozzle discharge coefficient; ξ_j is the coefficient of the jet losses in the tank; P_i is the emulsion pressure in the injector nozzle, Pa; ρ_O is the emulsion density, kg/m^3.

For ensuring intensive stirring, the emulsion jet should move in the turbulent regime with a quadratic resistance. Given the average velocity and cross-sectional area of the jet at a distance l_X from the injector nozzle, the Reynold's number is as follows:

$$Re = \frac{\varphi_i\sqrt{2P_i\rho_O d_i\left(l_X - d_i\right)}}{\eta_O\left(\frac{l_X}{d_i} - 1\right)\sqrt{\xi_j k_i}}, \qquad (2)$$

where φ_i is the injection rate coefficient; k_i is the coefficient of resistance to the liquid flowing from the injector; P_I is the emulsion pressure in the injector nozzle, Pa; ξ_j is the coefficient of the jet losses in the tank; ρ_O is the emulsion density, kg/m^3; d_i is the injector nozzle diameter, m; η_O is the dynamic viscosity of the emulsion, m^2/s; l_X is the distance from the injector nozzle to the considered jet section, m.

According to the Reynold's number (Fig. 5), the maximum distance l_{ef} between the injector and the section, which provides the necessary stirring intensity was determined.

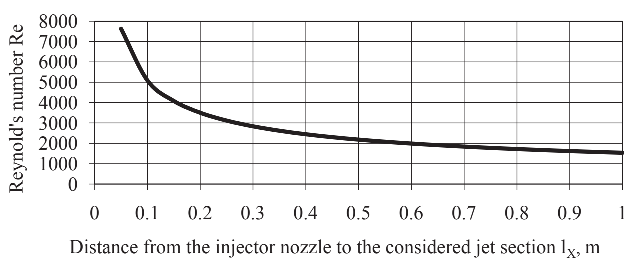

Fig. 5. The value of the Reynold's number by the jet length l_{ef} for the emulsion based on rapeseed oil at a temperature t = 40 °C, injector pressure P_I = 0.02 MPa, injector nozzle diameter d_I = 10 mm

According to l_{ef}, a certain number of injectors n_I was determined. The dependence of the effective jet length l_{ef} on the pressure in the injector nozzle and injector diameter, described by the second-order polynomial equation was revealed:

$$l_{ef} = 1.5388 - 4.6085\cdot10^{-5}P_i - 132.9672d_i + 8.4628\cdot10^{-12}P_i^2 + 0.0033P_i d_i + 2717.2856d_i^2. \qquad (3)$$

When using mixers, effective stirring is achieved in the emulsion jet of the length, determined by (3).

The key parameters of the mixer were determined as a result of theoretical and experimental studies, as typical for conical-bottom devices used in the chemical industry (Table 1).

Table 1

Rational parameters of mixers

Parameter	Inner tank diameter D_R, м					
	0.8	1.2	1.4	2.2	3.0	3.2
Rated capacity V_R, m^3	0.4	1	2	10	50	63
Injector installation diameter D_{II}, m	0.74	1.12	1.31	2.09	2.88	3.06
Injector nozzle diameter d_i, mm	20	25	30	30	30	30
Separator height H_S, m	0.95	1.12	1.57	3.05	7.65	8.45
Injector installation height h_{II}, m	30	41	43	53	61	68
Number of injectors n_I, pcs	4	4	4	4	4	4
Injector pressure P_I, MPa	0.01	0.01	0.02	0.03	0.04	0.05
Theoretical pump power N_T, W	61.3	83.4	173.4	318.6	490.5	685.5
Specific pump power n_T, W/m^3	153.3	83.4	86.7	31.9	9.8	10.9
Cycle duration τ_C, s	65.6	120.5	229.9	943.4	4065	4598.5
Stirring region height H_{SR}, m	0.06	0.08	0.09	0.11	0.12	0.14
Reaction region height H_R, m	0.66	0.69	1.08	2.31	6.66	7.39
Glycerol settling region height H_{GS}, m	0.23	0.35	0.4	0.64	0.87	0.92
Efficiency $E_{biodiesel}$, m^3/h	0.03	0.08	0.16	0.81	4.05	5.10

It was found that the turbulent regime in the emulsion jet will be provided at a pressure between 0.01 and 0.05 MPa and the mixer injector nozzle diameter between 10 and 35 mm.

The minimum energy consumption while the emulsion stirring and circulation is achieved at the hydraulic pump speed of 400 rpm and makes up 65 W.

The influence of the mixer parameters on specific power was determined:

$$n_T = 906.39 - 246.079V_R + 4.767d_i + 0.2271V_R^2 + 7.6232V_R d_i - 0.893d_i^2, \quad (5)$$

where n_T is the specific power spent on the emulsion circulation and stirring, W/m; V_R is the reactor capacity, m^3; d_i is the injector nozzle diameter, mm.

The research results also showed that the quality of biodiesel produced in mixers meets regulatory standards after one complete circulation, being the highest after threefold complete circulation.

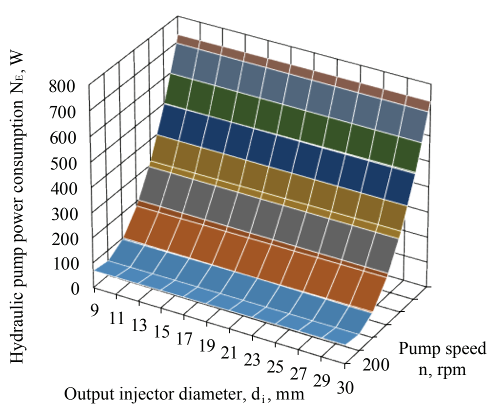

Fig. 6. Dependence of power N_E spent on the emulsion stirring and circulation on the hydraulic pump speed n and injector nozzle diameter d_i

In agricultural production, it is appropriate to divide biodiesel production into three main phases: oil production, biofuel production, biofuel storage. In order to reduce the number of manufacturing operations, it is necessary to combine biodiesel storage and methanol removal.

Biodiesel production equipment works as follows (Fig. 7): the circulation mixer 4 is filled with vegetable oil. Potassium methoxide from the tank for the catalyst 5 is fed to the circulation mixer 4. The pump 7 pumps out the emulsion from the bottom of the mixer 4. Then the emulsion is fed to the injectors, the operation of which provides the necessary stirring intensity. After transesterification, the emulsion resides in the mixer until the complete separation into glycerol and methyl ester fractions. The glycerol sediment level is controlled by a special device. Biodiesel is pumped out by the pump 8 through the pipe, which is installed on a special float device.

Biodiesel is stored in the tank 9, equipped with a methanol removing device. The proposed equipment reduces energy consumption for stirring and simplifies the equipment design. The quality of the resulting biodiesel meets regulatory standards.

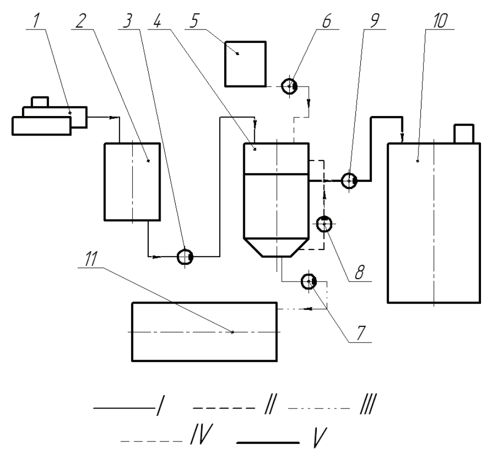

Fig. 7. A flowchart of biodiesel production using circulation mixers-separators: I —oil; II — emulsion; III — glycerol; IV — potassium methylate; V — biodiesel; 1 — press; 2 — oil storage tank; 3, 6, 7, 8, 9 — pumps; 4 — circulation mixer-separator; 5 — catalyst tank; 10 — biodiesel storage tank (tank storage); 11 — glycerol storage tank

Further research was focused on improving the biodiesel use in engines. It was found that the fuel spray angle increases from 21° to 30° when increasing the fuel temperature from 10 to 100 °C and almost reaches the diesel spray angle (Fig. 8).

Biodiesel temperature increase before injection enhances the spray characteristics, which improves emulsification and combustion efficiency of biodiesel.

Biodiesel heating temperature is limited by the operating temperature conditions of the high-pressure fuel pump. Therefore, the two-stage heating system for improving the biodiesel use was developed (Fig. 9).

The proposed system allows extending the temperature range of the biodiesel use due to preheating in a fuel tank to a temperature of 35–40 °C. At this temperature, the kinematic viscosity of biodiesel is less than 5 mm^2/s. The resulting viscosity provides fuel filtering in coarse and fine fuel filters. To further enhance combustion efficiency, biodiesel is heated before injection into the engine cylinders.

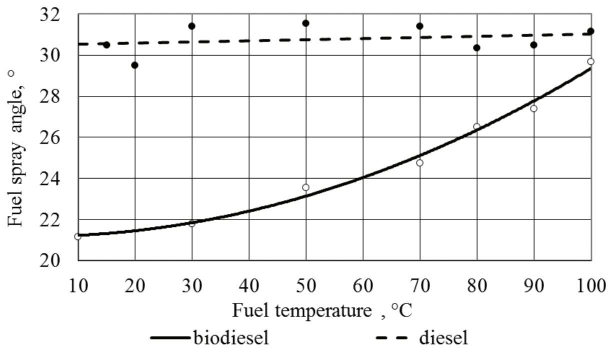

Fig. 8. Spray angle change depending on fuel temperature

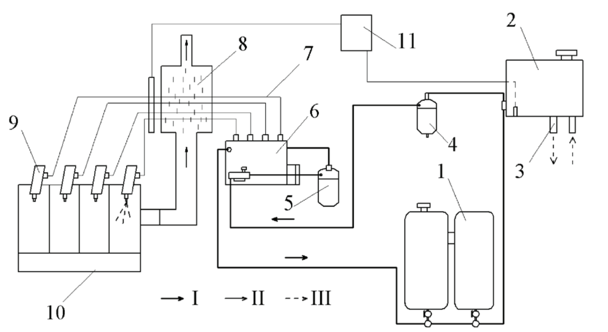

Fig. 9. Two-stage biodiesel heating system: I — biodiesel; II — exhaust gases; III — coolant; 1 — diesel tank; 2 — biodiesel tank; 3 — heat exchanger; 4 — coarse filter; 5 — fine filter; 6 — high-pressure fuel pump; 7 — high-pressure fuel lines; 8 — heating chamber; 9 — engine injectors; 10 — engine; 11 — temperature control unit

Production tests of machine-tractor units on the basis of the Kyi-14102 tractor with the D-245 engine were performed at an ambient temperature close to 0 °C. The research found that biodiesel overconsumption when plowing was 8.6 %, when disking – 9 %, as compared to diesel fuel (Table 2). The overconsumption corresponds to a difference between lower heating values of diesel and biodiesel – 8.25 %. During production tests, 1560 liters of biodiesel were spent.

The tests showed that machine-tractor units can operate on biodiesel while maintaining performance and power. Moreover, a slight fuel overconsumption is observed.

Table 2

Operating fuel consumption of machine-tractor units on the basis of the Kyi-14102 tractor using the biodiesel heating system

Operation	Biodiesel use, l	Fuel type and consumption, kg/ha		Biodiesel overconsumption, %
		diesel	biodiesel	
Plowing: Kyi-14102 + PRO-3	200	15.9	17.2	8.6
Disking: Kyi-14102 + BDV-3	670	5.7	6.3	9.0
Sowing: Kyi-14102 + Great Plains-1,5	380	8.7	9.8	12.6

6. Discussion of the research results on the parameters of equipment for production and use of biodiesel

The presented materials are a continuation of the research conducted within the research topics «Development of Mechanical and Technological Foundations of Resource-Efficient Organic Production of Agricultural Products and Biofuels in Agricultural Ecosystems with a High Level of Energy Self-Sufficiency» (state registration number – 0114U000660) and «Creation of Mechanical and Technological Foundations of Resource-Efficient Production and Use of Biofuels in Energy Self-Sufficient Agricultural Ecosystems» (state registration number – 0115U003375).

The use of circulation mixers-separators allows biodiesel production by the simplified technology in agricultural production. However, this technology needs to be improved in terms of developing the systems for complete removal of fatty acid methyl esters from the mixer in the field.

The cost of biodiesel production ranged from 12 to 13 UAH/l. The cost of sub-standard oil made up 9.7 UAH/l, potassium methylate – 110 UAH/l. The resulting biodiesel characteristics were in accordance with DSTU 3868-99 and DSTU 6081:2009.

Application of the developed two-stage biodiesel heating system and compliance with a reasonable heating temperature range extend the temperature range of using pure biodiesel and reduce its consumption to 7 %. The use of the two-stage heating system provided a higher biodiesel use efficiency of 633.6 UAH/t.

A research of the impact of the biodiesel use on emissions reduction and engine life of agricultural machinery should be carried out in future.

The research results confirmed the efficiency of the developed equipment and the results of theoretical and experimental studies.

7. Conclusions

1. For ensuring the required stirring intensity in biodiesel production by transesterification, the emulsion jet in the mixer should move in the turbulent regime. The turbulent regime in the emulsion jet will be provided at a pressure between 0.01 and 0.05 MPa and the injector nozzle diameter between 10 and 35 mm. Minimum energy consumption during the emulsion stirring and circulation is achieved at the hydraulic pump speed of 400 rpm and makes up 65 W for the mixer with a capacity of 1.4 m^3.

2. The key parameters of the mixer were determined as typical for conical-bottom devices used in the chemical industry. For agricultural production, the mixer with a capacity of 1.4 m^3, optimum injector diameter of 30 mm, the number of injectors of 4, operating excessive pressure of 0.02 MPa, theoretical hydraulic pump power of 173.4 W, efficiency of 0.16 m^3/h of biodiesel is the most suitable.

3. In agricultural production, it is appropriate to divide biodiesel production into three main phases: oil production, biofuel production, biofuel storage. In order to reduce the number of manufacturing operations, it is necessary to combine biodiesel storage and methanol removal.

The emulsion is fed to the mixer injectors, the operation of which provides the necessary stirring intensity. After transesterification, the emulsion resides in the mixer until the complete separation into glycerol and methyl ester fractions. Biodiesel is stored in the tank, equipped with a methanol removing device.

4. The fuel spray angle increases from 21° to 30° when increasing the fuel temperature from 10 to 100 °C, which enhances the spray characteristics and improves emulsification and combustion efficiency of biodiesel. The two-stage heating system, which allows extending the temperature range of the biodiesel use due to preheating in a fuel tank to a temperature of 35–40 °C for improving the biodiesel use efficiency was developed. To further enhance combustion efficiency, biodiesel is heated to a temperature of 100 °C before injection into the engine cylinders.

5. Production tests of machine-tractor units on the basis of the Kyi-14102 tractor with the D-245 engine, equipped with the biodiesel heating system revealed that biodiesel overconsumption when plowing was 8.6 %, when disking – 9 %. The overconsumption corresponds to a difference between lower heating values of diesel and biodiesel – 8.25 %.

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