ELECTROSTATIC TREATMENT OF AGRICULTURAL CROPS WITH AN UNMANNED ELECTRIC DEVICE

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One of the options for improving the efficiency of the machine and tractor unit in the field is the use of course indicators, thrusters, hydraulic autopilots and other equipment. However, these devices do not exclude environmental pollution by exhaust gases and the presence of significant operating costs for fuel and lubricants. In this regard, the paper proposes an electric-powered unmanned device (EPUD), which can perform the tasks with high accuracy (deviations from the set course average 16 cm) due to autonomous movement on GPS/GLONASS satellite radio navigation signals on agricultural lands. For the effective application of liquid agents to agricultural crops, a device is proposed that provides an electric charge of the introduced fine aerosol, which is installed on the EPUD and reduces the electrical energy consumed by 23.5% compared to existing analogues. All this, combined, will reduce operating costs up to 10%, as well as improve the environmental performance of crop spraying. Based on the conducted studies of the EPUD, its design was developed and a prototype with a software and hardware part was created. A device for the electric charge of the introduced aerosol, which makes it possible to increase the uniformity of the aerosol application on the plant, has been developed and investigated. The effectiveness of the developed technical solution had been proved by laboratory and field tests.

Keywords:electrostatic field; fine aerosol; radio navigation systems; spraying; unmanned electric device

1   INTRODUCTION

Appropriate spraying of agricultural crops is one of the main indicators of productivity. Proper protection requires equipment that can effectively implement this technological process with the lowest energy costs [1- 3]. Experience of foreign authors such as Pilli et al. [4], Bhong and Pawar [5], Ericson and Åstrand [3], Shaikh et al. [6], Gabitov et al. [7], Rajesh et al. [8], Chaitanya et al. [9] shows that autonomous devices due to intelligent systems allow for more efficient execution of technological operations, which leads to a reduction in the cost of production. Currently, there is no mass production of autonomous robotic devices capable of performing technological operations through intelligent systems. Nevertheless, leading enterprises of various countries, such as Amazone (Germany), John Deere (USA), Topcon (Japan), Wall-Ye (France), Ladybird (Australia), Agrointelli (Denmark), Edete Artificial Pollination (Israel), Priva (Netherlands) are actively conducting research and developing prototypes of intelligent mobile robotic devices for the needs of agricultural production. The use of electric devices makes it possible to eliminate the cost of fuel and lubricants and reduce the costs associated with the maintenance of the machine and tractor unit. "The battery, as a power source, does not have the risk of fuel and lubricants spillage, and its recharge can be carried out through existing solar technologies that have availability and choice in the market," notes Md. Didarul Islam Sujon, a researcher in the Department of Electrical and Computer Engineering, North South University, Bangladesh [10]. Based on the analysis carried out and the trend in the development of mobile equipment, which consists in the transition from internal combustion engines to electric motors, the paper proposes an EPUD capable of performing the tasks set using a hardware and software complex. The movement of the EPUD on a given course employing radio navigation signals makes it possible to ensure the autonomy of its operation, and therefore, to eliminate errors associated with the physical and professional capabilities of the operator. For the effective operation of the EPUD, the introduction of pesticides is proposed by using a fine aerosol (the diameter of the drops does not exceed 210 microns), which, in comparison with traditional full-volume spraying with the same consumption of pesticides (fertilizers) per unit area, covers the entire surface of the treated crop evenly and will also increase the productivity of the plant.

1.1   Purpose of the research

Reduction of operating costs for the application of liquid fertilizers and pesticides through the development and implementation of an unmanned electric unit with an electric charging device for the introduced fine aerosol.

Research objectives are

- to develop a design and create a prototype EPUD with software and hardware that allows autonomous movement on the field;
- to develop and research a device for an electric charge of the introduced aerosol;

- to conduct laboratory and field tests of the developed EPUD with the device of electric charge of the introduced fine aerosol.

2 METHODS

The EPUD is a universal, self-contained electric chassis with a device for applying liquid fertilizers and pesticides in an electrostatic field (Fig. 1). The engine of the device is represented by a solid rectangular frame withindependently controlled wheels 1, each is equipped with a separate electric drive with a brushless DC motor. A fine aerosol generator is installed in the container with the working solution 2. The aerosol along the main line 7 of the device through the nozzles 3 reaches the surface of the treated culture. The power source of the EPUD is lithium-ion batteries 4. When working in open ground conditions, there is the possibility of an additional source of energy due to the solar panel 6. The EPUD automatically follows the set course and introduces liquid fertilizers and pesticides through the control and navigation system 5.
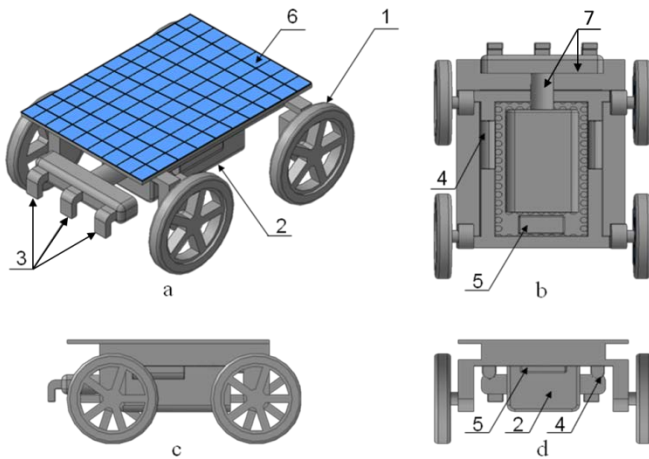

Fig. 1. The EPUD for processing agricultural crops with electrically charged liquid fertilizers and pesticides: a) general view; b) bottom view; c) side view; d) front view.

The rotation of the electric unit is carried out due to the difference in the speed of rotation of the external rotors of the brushless DC motors (BDCM) of each wheel, the algorithm of which is laid down in the control system (Fig. 2).
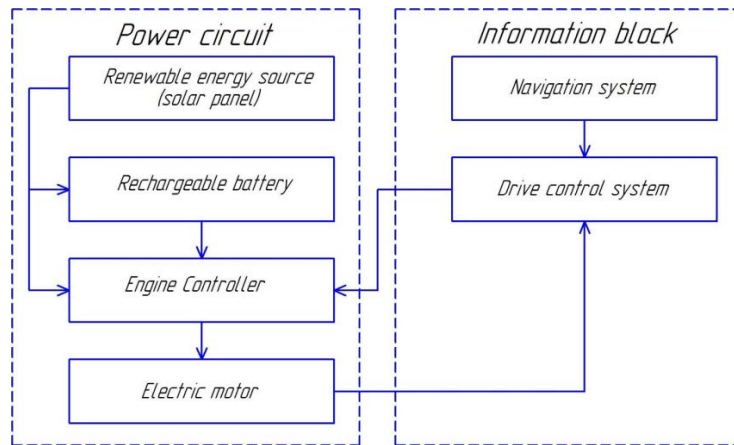

Fig. 2. Functional diagram of the electric device control system.

The control system controls and controls the traction drive system as a whole (wheel speed, engine torque, breaker currents, and the route of the set course). The control system of the EPUD consists of two main parts: the power circuit and the information block. The power circuit includes a battery pack, a renewable energy source (solar panel), a motor controller, and a BDCM. The information block includes the navigation system and the drive control system, respectively. Nowadays the most common method of applying liquid preparations is full-volume spraying (dispersion >500 microns). Its main drawback is the runoff of the drug from the plants resulted from excessive wetting, which leads to an increase in the cost of production and soil contamination. To eliminate this drawback, it is proposed to apply liquid fertilizers and pesticides with a fine aerosol (the diameter of the drops does not exceed 210 microns), which, in comparison with full-volume spraying, with the same consumption of pesticides (fertilizers) per unit area, covers the entire surface of the treated crop evenly. In closed ground conditions, a high efficiency of using a dispersion of <210 microns for processing agricultural crops are observed, when in open ground conditions a significant disadvantage is the uneven deposition of aerosol on the treated surface of the plant. One of the ways to eliminate this drawback is to give the aerosol particles an electric charge. In an electrically charged aerosol, additional forces of interaction of particles arise – electrostatic scattering and mirror image, which contributes to the

equalization of the concentration by volume while increasing the deposition rate [11]. The principle of electrostatic spraying is as follows (Fig. 3): air is pumped into the container with the working fluid using a vortex fan, the generator from the working fluid forms a fine aerosol. Under the influence of vortex flows, the aerosol is directed to the nozzles, at the ends of which electrodes are installed, passing through which the aerosol acquires a charge and enters the processing zone of agricultural crops.
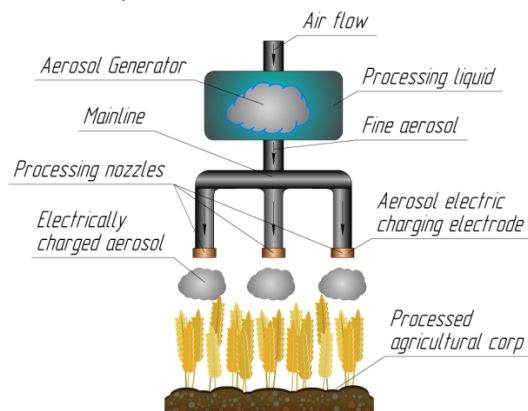

Fig. 3. Processing of agricultural crops with fine aerosol in an electric field.

Nowadays it is known to use electric charging of liquid-air droplets by applying a constant high potential to the electrode (electrostatic induction) [1, 12]. However, this method of electric charging has its drawback – the low efficiency of charge accumulation by sprayed drops, which ultimately requires an increase in the electric potential at the electrode, which affects the uniformity of thedistribution of the applied drug to the plant. The sequence of operation of the system is as follows. The boundaries of the processed field are set, then the EPUD starts moving as the system continuously receives radio navigation signals from satellites, based on which the current position of the EPUD is determined. Also, based on these signals, the control program calculates the amount of deviation from the specified trajectory. In this case, signals are generated, which in the form of a voltage are transmitted to the electric drive (an electric DC motor) of each wheel with an operating voltage of 48 V. Due to the difference in the speed of rotation of the wheels, the EPUD rotates at the required angle, i.e., it provides a manoeuvre for approaching the current trajectory of the EPUD to the necessary one, which corresponds to the principle of parallel operation of the unit on the field [13, 14]. The mismatch between the actual position of the EPUD and the specified trajectory is determined by the current coordinate and the calculated trajectory of the unit. We assume that the radius of the return of the EPUD to a given course when it deviates will be equal to the value of the deviation A, which is determined by the distance of the perpendicular from the geometric centre of the unit to the line of the given path. For theoretical research and justification of the design and technical parameters of the device, it is necessary to draw up a kinematic scheme of the movement of the EPUD in the field (Fig. 4). When drawing up the kinematic scheme of the movement of the EPUD, the following assumptions are made: the centre of mass of the device is located in the geometric centre of the body; both wheels of each side rotate at the same speed and always touch the support surface
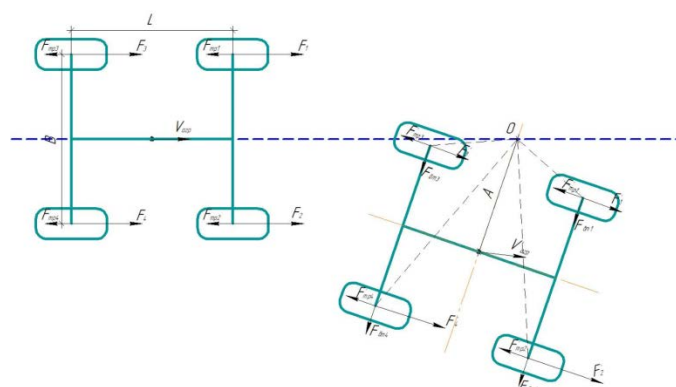

Fig. 4. Kinematic diagram of the movement of the EPUD: a) at a given course; b) at the time of deviation from the specified course.

In the rectilinear motion of an EPUD moving on a given course, the speed (the speed of the centre of mass) is equal to the speed of all its wheels:

$$V_1 = V_2 = V_{dev}$$

(1)

where V_1 is the speed of the left side of the EPUD, m/s;

V_2-speed of the starboard side of the EPUD, m/s;

V_{dev} – the speed of the EPUD, m/s.

According to the theory of cars and tractors [15], the radius of the side turn R_{turn} will be determined by the following expression:

$$R_{turn} = \frac{B(V_2 + V_1)}{2(V_2 - V_1)}$$

(2)

where B is the transverse wheelbase, m.

The speed of the device R_{dev} is accepted according to the agrotechnical requirements. When the EPUD deviates from the set course, it is assumed that the speed of the left (lagging) side V1 is const and the turning radius R_1 is equal to the deviation value A, which is determined by the current coordinate and the calculated trajectory of the device. Accordingly, to return to the required trajectory, it is necessary to determine the speed of the right (running) side V_2 (Fig. 4):

$$V_2 = \frac{V_{dev} \cdot B + V_1 \cdot A}{A}$$

(3)

where A is the value of the deviation of the EPUD from the set course (return radius), m

Based on the kinematic scheme, a mathematical model of the EPUD movement is compiled, the main element of which is the wheel motor, which is a direct drive based on a brushless DC motor.

A brushless DC motor in a mathematical model is described by the equations [16,17]:

$$u_k = r_k i_k \left(\theta_m \right) + L_k \frac{di_k \left(\theta_m \right)}{dt} + \psi_{0k} \left(\theta_m \right) \omega$$

$$M_k = \psi_{0k} \left(\theta_m \right) i_k \left(\theta_m \right)$$

$$M = p \sum_1^m M_k$$

$$\frac{d\omega_m}{dt} = \frac{1}{J} \left(M - M_H \right)$$

$$\frac{d\theta_m}{dt} = \omega_m$$

$$\omega = p\omega_m$$

(4)

where u_k, $i_k(\theta_m)$, $\Psi_{0k}(\theta_m)$, M_k — instantaneous voltage (V), current (A), flow coupling (W- instantaneous voltage (V), current (A), flow coupling (- instantaneous voltage (V), current (A), flow coupling (Wb) and electromagnetic moment of the short phase (H*m); and electromagnetic moment of the short phase (H*m); b) and electromagnetic moment of the short phase (H*m);

r_k, L_k — resistance (Ohms) and inductance of the short phase (H);

ω, ω_m — the angular frequency of the voltage (current) in phase (rad/s) and the angular speed of the motor shaft (rad/s);

M, M_H — total electromagnetic torque (H*m) and motor shaft load torque (H·m);

J, p — the moment of inertia on the motor shaft (kg*m2) and the number of pairs of motor poles.

The equation of motion of the EPUD has the following form:

$$m\frac{dV}{dt} = F_1 + F_2 + F_3 + F_4 - F_{c1} - F_{c2} - F_{c3} - F_{c4} - F_{lf1} - F_{lf2} - F_{lf3} - F_{lf4}$$

(5)

where $m\dfrac{dV}{dt}$ - dynamic drive force, H;

$F_1 \dots F_4$ – active forces (developed by each EPUD), H;

$F_{c1} \dots F_{c4}$ – longitudinal forces (friction forces), H;

$F_{lf1} \dots F_{lf4}$ – lateral forces, H.

Since each wheel of the EPUD is equipped with its own drive, the longitudinal forces (friction forces) F_c will be defined as the rolling friction forces of the driving wheel [18]

$$F_c = \frac{k \cdot N}{R} \tag{6}$$

where k – the value of the longitudinal drift, m;

N – reaction force of the reference surface, H;

R – wheel radius, m.

The lateral forces are determined by:

$$F_{lf} = \phi \lambda G_{dev} \tag{7}$$

where φ – coefficient of adhesion of tires to the bearing surface;

λ – dynamic wheel load factor;

G_{dev} – gravity (weight) of the device, H.

The study proposes a method for improving the efficiency of electric charging of aerosol droplets, which consists of using a resonant transformer and periodically interrupting the operation of the resonant transformer generator.

Fig. 5 shows a block diagram of the proposed device for electric charging of liquid-air droplets.
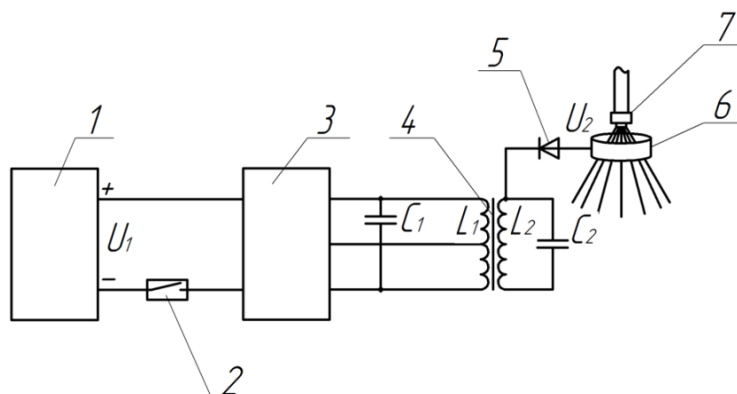

Fig. 5. Block diagram of the device for electric charging of liquid-air droplets.

The device for electric charging of liquid-air droplets consists of a power source 1, an electronic key 2 that provides a break in the supply circuit with a low frequency, a multivibrator 3 with a high-frequency oscillating circuit L_1C_1, and the inductance L_1 is a low-voltage winding of the resonant transformer 4, the inductance L_2 is a high-voltage winding of the resonant transformer 4 and forms a second oscillating circuit L_2C_2 with the capacitor C_2, to which the diode 5 and the electrode 6, which is a cylinder, are connected in series and is installed behind the sprayer 7.

The principle of operation of the proposed device for electric charging of a liquid-air mixture is described as follows. A multivibrator 3 with an oscillating circuit L_1C_1 generates a carrier (modulated) signal ω_1, and an electronic key 2 that breaks the supply network with a low frequency generates a modelling signal ω_2. Next, the resulting amplitude-modulated voltage is increased by a resonant transformer 4, rectified by a diode 5, and fed to electrode 6. Fig. 6 shows the time dependence of the potential on the electrode surface.
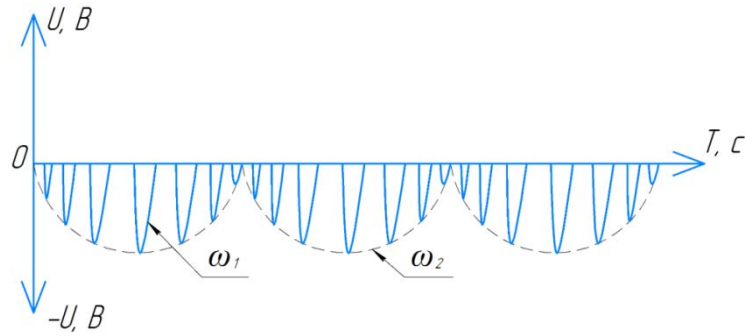
Fig. 6. Time dependence of the potential on the electrode surface.

The proposed device makes it possible to increase the efficiency of electric charging of liquid-air droplets by applying a potential to the electrode that changes over time.

3   RESEARCH RESULTS

Based on the theoretical descriptions of the EPUD and the device for electric charging of liquid-air droplets, their comprehensive study was carried out in the object-visual modelling environment Matlab (Simulink), according to which the experimental design of the BPEA and the device for electric charging of liquid-air droplets were created (Fig. 7).

Fig. 7. Developed by the EPUD for the treatment of agricultural crops with a fine aerosol in an electrostatic field.

Development and debugging of the electric unit control program are performed in the Processing/Wiring language. Fig. 8 shows the developed schematic diagram of the device for electric charging of liquid-air droplets.
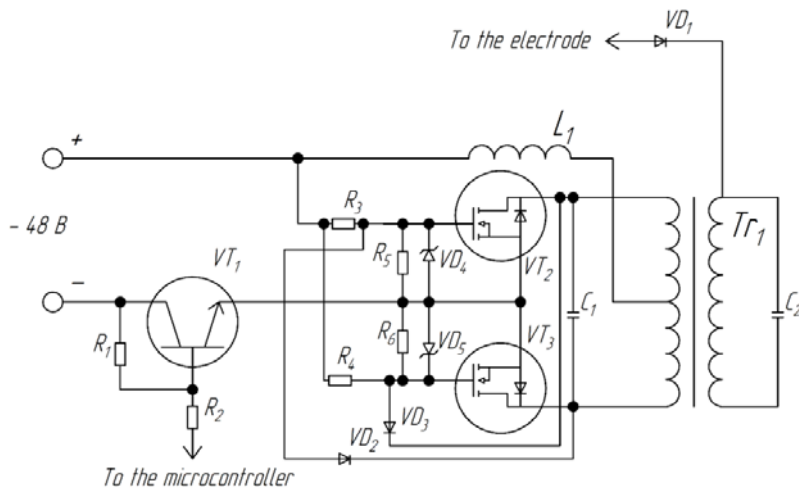

Fig. 8. Schematic diagram of the device for electric charging of liquid-air droplets: $R_1…R_6$ – resistor; L_1 – choke; $VT_1…VT_3$ – transistor; $VD_1…VD_3$ – diode; VD_4, VD_5 – zener diode; C_1, C_2 – high-voltage capacitor; Tr_1 – step-up transformer.

The technical characteristics of the EPUD and the device for electric charging of liquid-air droplets are presented in Table 1.

Table 1. Technical characteristics of the EPUD and the device for electric charging of liquid-air drops.

No	Name of the value	Meaning
1.	Dimensions (length / width/height)	*1740/1500/950 mm*
2.	Track	*1050 mm*
3.	Wheelbase	*900 mm*
4.	Ground clearance	*500 mm*
5.	Weight without load	*140 kg*
6.	Maximum permitted weight	*260 kg*
7.	Power reserve	*Up to 45 km*
8.	Drive type	*4x4*
9.	Power	*4*750 W*
10.	Speed of the device movement	*5-15 km/h*
11.	Supply voltage	*48 V*
12.	Tank capacity for cold mist generator	*100 l*
13.	Consumption of the cold mist generator	*10 l/h*
14.	Capture width	*1.35 m*
15.	Device power supply voltage	*48 B*
16.	Power consumption of the device for electric charging of liquid-air droplets	*15 W*
17.	Voltage (potential) at the electrode	*3…5 kW*
18.	The polarity of the voltage (potential) at the electrode	minus
19.	Resonant frequency of the oscillatory circuit of the device for electric charging of liquid-air droplets	52 kHz
20.	Installation capacity	at V_{min} – 0.68 *Ha/h* at V_{max}-2.02 *Ha/h*
21.	Maximum power of the solar panel	*400 W*
22.	GPS/GLONASS Receiver Accuracy	*Up to 15 cm*

The effectiveness of the developed technical solution was proved by field tests. The tests were carried out in the fields of a peasant (farmer) farm in the Karmaskalinsky district of the Republic of Bashkortostan. During 15 days, 10 passes were made at different soil humidity in different operating modes, the results of which are shown in Fig 9
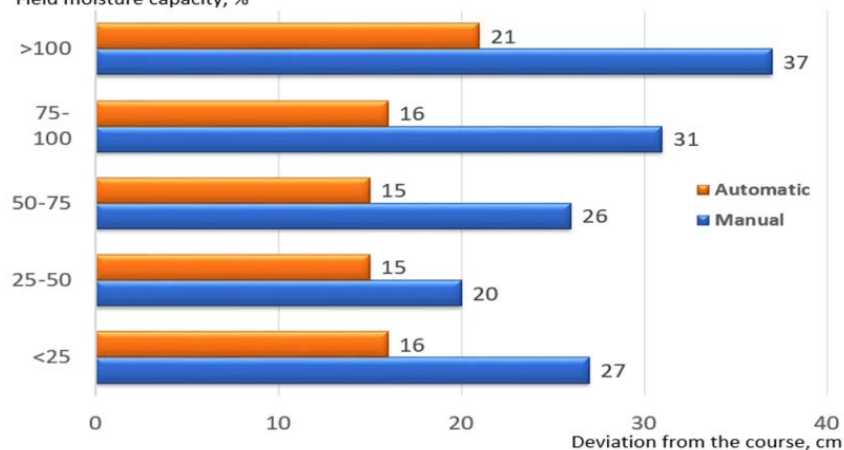
Fig. 9. Average deviation of the EPUUD from the course at different modes of movement and field moisture capacity.

In automatic mode, the electric device was controlled by the GPS/GLONASS navigation satellite control system, and the manual mode meant remote control by the operator on the course indicator.

One of the above statements is the low power consumption of a device that charges drops with an alternating electrostatic voltage, compared to a device that charges drops with a constant electrostatic voltage. Fig. 10 shows the dependence of the power consumption of the aerosol electric charging device on the supply voltage obtained during the research.
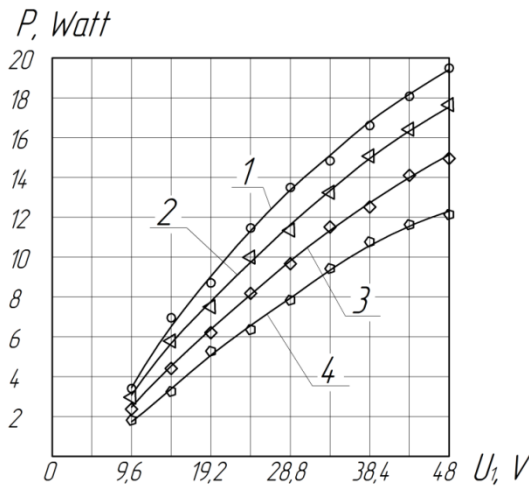

Fig. 10. Dependence of the power consumption P on the supply voltage of the device U_1 for electric aerosol charging: 1 - at the interrupt frequency $\omega_2=0$ Hz; 2 - at the interrupt frequency $\omega_2=30$ Hz; 3 - at the interrupt frequency $\omega_2=60$ Hz; 4 - at the interrupt frequency $\omega_2=90$ Hz.

When setting the value of the interrupt frequency ω_2, the pulse duration t was selected in such a way that with the end of the damped oscillations, the next oscillations began. According to the obtained research results, the power consumption P decreases with an increase in the interrupt frequency ω_2. However, at an interrupt frequency of more than $\omega_2=100$ Hz, a deterioration in the process of electric charging of liquid-air droplets is observed (carrier frequency $\omega_1=52$ kHz). Thus, the electric charging of droplets with an alternating electrostatic voltage of negative polarity allows you to reduce the electrical energy consumed.

One of the parameters that make it possible to evaluate the effectiveness of spraying plants in an electrostatic field is the specific deposition density of electrically charged droplets N_{spd}, which was determined by the inertial method in the absence of wind. Liquid-air drops were deposited on slides coated with a mixture of boric ointment and transformer oil in a ratio of 2.5:1. The glasses were placed at the level of the leaves directly on the path of the EPUD passage. According to the obtained values of N_{spd} at different velocities of the V_{EPUD}, the average value of the specific deposition density N_{spd} was determined. During the experiments, the speed V_{EPUD} of the EPUD movement (from 5 m/s to 12 m/s) and the voltage U (from 1 kW to 4 kW) applied to the electrode changed. At the same time, the specific charge of liquid-air droplets was determined (the ratio of the charge of the droplets to its mass) by the following formula:

$$Q_{spd}= U_k(C+C_{в})/\textstyle\sum m, \qquad (8)$$

where U_{k} - the potential of the metal vessel in which the sprayed droplets accumulated, relative to the ground, B;

C – electric capacity of a metal vessel relative to the ground, F

$C_{в}$ – input electric capacity of the measuring device, F;

m – the mass of the liquid worked to the bottom in the metal vessel, kg.

Based on the obtained values of the specific charge of liquid-air droplets, the dependence shown in Fig. 11 is constructed.
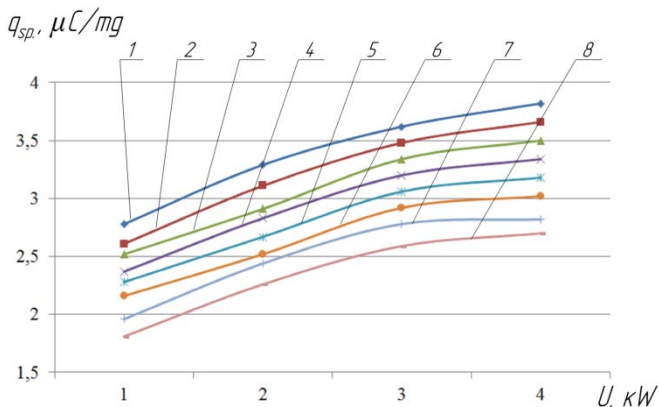

Fig. 11. Dependence of the specific charge of the q_{spd} droplets on the voltage at the electrode U at different speeds of movement of the EPUD V_{EPUD}: 1-5 m/ s; 2 – 6 m/ s; 3-7 m/ s; 4-8 m / s; 5-9 m / s; 6-10 m / s; 7-11 m/s; 8-12 m/s.

According to the obtained dependence of the specific charge of the drops $q_{уд}$ on the voltage at the electrode U at different speeds of movement of the EPUD V_{EPUD}, it can be seen that with an increase in the speed of movement of the EPUD V_{EPUD}, and, consequently, with an increase in the flow rate of the liquid Q, the specific charge of the

drops $q_{y\partial}$ decreases, which is associated with an increase in the number of droplets passing through the electrostatic field.

When studying the efficiency of droplet deposition on slide glasses according to the above method, two methods of electric charging of droplets were also compared:

- with a constant electrostatic voltage;

- with variable (in amplitude) electrostatic voltage (Fig. 12).

As can be seen from the obtained research results, when applying a potential variable in amplitude (variable electrostatic voltage) U=3 kW to the electrode, the maximum value of the average specific density of electrically charged droplets that worked to the. bottom is observed, $N_{aspd.}$=284 pcs / cm^2 (Fig. 12), which is defined as the sum of the specific deposition densities obtained at different speeds of the EPUD movement, divided by the number i of the EPUD movement speeds (N_{aspd} =$\sum N_{sp.i}$/i). The decrease in the average specific density of deposition of electrically charged droplets with a further increase in voltage is associated with a decrease in the diameter of the droplets due to their additional crushing in the electrostatic field, as a result, the droplets become sensitive to a small movement of air masses.
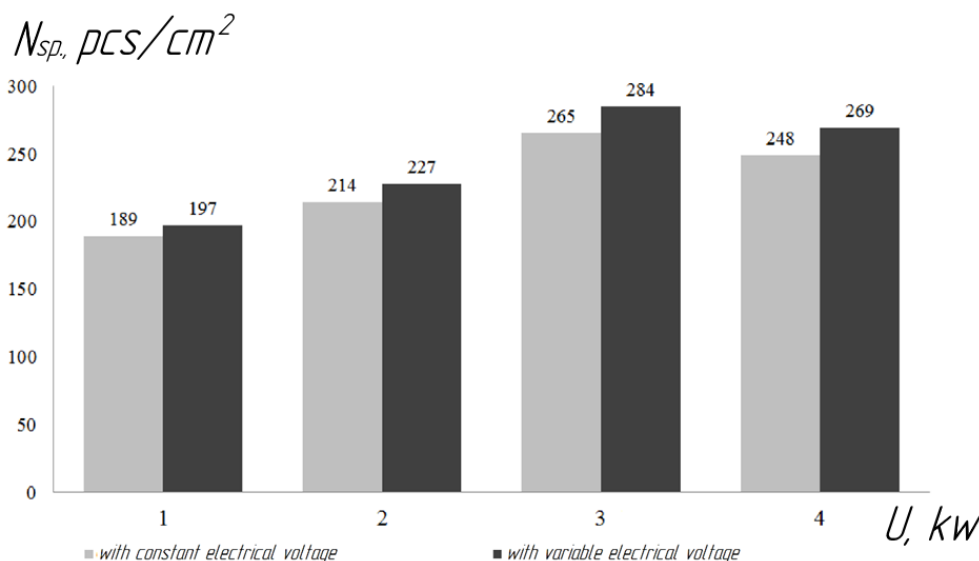

Figure 12: Dependence of the average specific density of deposition of electrically charged droplets Naspd from the voltage at the electrode U at a constant

Fig. 13 shows the dependence of the specific density of deposition of electrically charged drops of Nsp. from the speed of movement of the EPUD V_{EPUD} at the voltage at the electrode U=3 kW. As we can see, at the speed of movement of the EPUD V_{EPUD} = 9 km / h, the greatest efficiency of spraying plants with Nsp is observed = 311 pcs/cm^2.
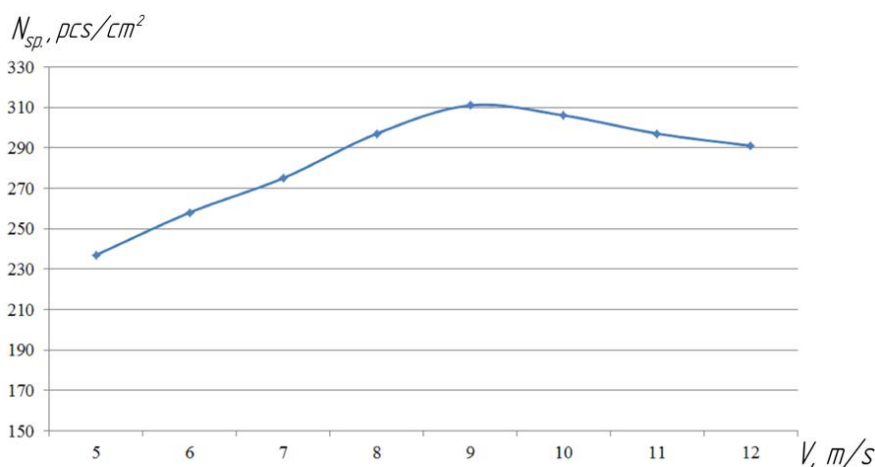

Figure 13: Dependence of the specific deposition density of electrically charged droplets Nsp from the speed of movement of the EPUD V_{EPUD} at the voltage at the electrode U=3 kW.

4 DISCUSSION

Field tests have shown that the deviation of the electric device from the course in the automatic control mode is on average 16.6 cm. This accuracy is sufficient for the application of liquid fertilizers and pesticides [15, 19,20].

As it can be seen from the presented dependencies, the use of electric charging of liquid-air droplets with variable electrostatic voltage reduces the electrical energy consumed by 23.5% compared to applying a constant amplitude potential (voltage) to the electrode. In addition, the fine aerosol envelops all processed objects more effectively in

the area of direct processing. This method leads to the most economical and efficient method of processing agricultural crops with liquid fertilizers and pesticides compared to processing without electric charging or with treatment with constant electrostatic voltage and it can be used in precision farming systems [11, 21,22]. The conducted studies have shown that when applied to the electrode with a variable amplitude potential (variable electrostatic voltage) U=3 kW, the maximum value of the average specific deposition density of electrically charged droplets N_{spd} = 284 pcs/cm^2 is observed.

In the course of the research, it was found that the greatest efficiency of plant treatment by electric charging of sprayed drops with a variable electrostatic voltage of negative polarity was observed at the voltage at the electrode U=3 kW and the speed of movement of the EPUD V_{EPUD} = 9 km/h. The value of the specific density of deposition of electrically charged droplets was N_{sp}= 311 pcs/cm^2.

5 CONCLUSIONS

A device for electric charging of fine aerosol intended for spraying agricultural crops has been developed and investigated, which, along with well-known analogues, reduces the consumption of electrical energy by periodically interrupting the power supply circuit of the device.

The absence of exhaust gases and runoff of liquid fertilizers and pesticides from plants to the soil makes it possible to get a more environmentally friendly final product and reduce the cost of its production.

450 thousand rubles were spent on the development of a prototype of the proposed technical solution. With this budget, the EPUD is equipped with batteries with a capacity of 20 Ah, which allows having a power reserve up to 45 km on a single charge with the ability to process up to 2.2 hectares per hour.

According to technical and economic calculations, the developed technical solution in comparison with traditional methods of plant processing makes it possible to reduce operating costs by up to 10 %. The payback period will be about 2 years, taking into account the processing of more than 300 hectares per year.

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