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THE EFFICIENCY OF USING AGRAS DRONES FOR SPRAYING, THEIR DESIGN, TECHNICAL AND TECHNOLOGICAL FEATURES

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Agrotechnical operations on spraying crops from diseases and pests are an important part of almost any agricultural technology. They make up a significant part of the cost of all agricultural technology and, as a result, the cost of the final product. The use of unmanned aerial vehicles (UAVs) has a huge potential in agriculture and every year the interest in their use grows primarily in the implementation of the tasks of precision farming.

The object of research in this article is the process of spraying work areas with Agras unmanned aerial vehicles.

The aim of the study is to study the effectiveness of DJI's Agras drones in spraying cultivated plants with pesticides, diseases, weeds and to establish their design and operating features.

The objectives of the work are to establish the design and mode features of unmanned aerial vehicles Agras T16, T20 and T30; to find out their productivity on spraying of cultural sites and to substantiate possible reserves in increase of productivity of drones-sprayers.

The research methodology is based on the method of cognitive activity, mathematical modeling, methods of analysis and synthesis of both information from official sources and information from the works of other researchers.

The scientific work considers the excellent technical and operational features of hexacopters Agras T16, T20 and T30. The performed analysis allows us to assert the dynamics in improving the efficiency of their use. The practical aspects of their use in spraying with plant protection products, the choice of the required mode of exploitation are substantiated.

It is noted that the performance of sprayers depends on the diameter of the swing of the rotors, which create a downward flow of air, the number of rotors and the height above the crop surface. Their maximum permissible speed is limited by the performance of the installed pumps, the capacity of the nozzles to ensure a given rate of discharge of the working drug, by properties of substances of the tank mixture, etc.

The calculation of operational productivity Sparaying Drones Agras T16, T20 and T30 at the length of the runs of sections 750 and 1000 m is given. Productivity of Sparaying Drones Agras T16, T20 and T30 at a run length of 1000 m is obtained, respectively, 7.65; 8.29 and 10.5 ha/h. With the reduction of the run length to 750 m, the productivity of all Sparaying Drones Agras T16, T20 and T30 increases, respectively 8.40; 9.10 and 11.06 ha/h. Analyzing the balance of time of change of Agras drones in percentage it was found, that about 25 % is due to downtime of unregulated time, which is caused by technical malfunctions, organizational problems and weather conditions.

The most important reserves in increasing the productivity of DJI's Agras drones for spraying cultivated plants with pesticides, diseases and weeds have been noted.

Key words: *unmanned aerial vehicle, hexacopter, Agras, drone-sprayer, spraying, flight planning, shift time utilization factor, shift time balance, drone performance.*

F. 11. Fig. 3. Table 3. Ref. 23.

1. Introduction

Agrotechnical operations on spraying crops from diseases and pests are an important part of almost any agricultural technology. These operations, as a rule, constitute a significant part of the cost of all agricultural technology and, as a consequence, the cost of the final product. Also, it should be taken into account that spraying with chemicals significantly affects the environmental situation in the field, which, in turn, affects the quality of the final product and further soil fertility. Obviously, the correct calculation of the rate of application of the working solution during spraying, as well as its differentiated application is an important task in the cultivation of agricultural products.

2. Formulation of the problem

At present, trailed and self-propelled boom sprayers, small aircraft and unmanned aerial vehicles (UAVs) are used in the technology of growing cultivated plants. For almost the last 50 years, the approach to the introduction of plant protection products in the field has not changed dramatically. And the further development of spraying tools is aimed at improving the accuracy of work, reducing the cost of pesticides, increasing the speed of field treatment.

Undoubtedly, each of the technical plant protection products used has its advantages and disadvantages. If we talk about the advantages of UAVs, it makes sense in the context of comparing agro drones with ground equipment, namely with trailed and self-propelled sprayers. Compared to any wheeled sprayer, the drone solves the problem of trampling crops by 100%, damage to plants by sprayer booms, lack of soil compaction, the ability to work immediately after rain, and so on. It is also clear that, for example, a drone is not able to completely replace a wheeled sprayer, given its productivity.

Small aircraft for the application of pesticides, for example, will disappear from the market as unpopular in the near future, as the UAV market is rapidly evolving, displacing it. It should also be mentioned that the use of small aircraft, depending on the type of manned aircraft, requires the presence of runways and appropriate infrastructure.

The advantages of UAV spraying are their ability to spray areas with problematic topography. For example, on steep slopes, where only people with hand sprayers can work. Local problem areas in large fields are also more profitable to treat locally than using a conventional wheeled sprayer.

With the help of UAVs in agriculture you can solve such tasks: creating electronic field maps (building a 3D model of fields); inventory of agricultural land; assessment of the scope of work and control of their implementation; optimal construction of irrigation and reclamation systems; operational monitoring of crop condition (UAV allows you to quickly and efficiently build maps on the stairs), as well as to determine the normalized vegetation index NDVI (Normalized Difference Vegetation Index) in order to effectively apply fertilizers; assess the similarity of crops; to forecast crop yields; to carry out ecological monitoring of agricultural lands; protection of agricultural lands; spraying crops with chemicals to control pests and diseases; assess the chemical composition of the soil. In addition to the agricultural sector, drones can be used in surveying and topography, mining, as well as be used as a mobile repeater and more.

Thus, the use of UAVs in agriculture has great potential and every year the interest in their use grows primarily in the implementation of the tasks of precision farming.

The efficiency of agrodrons in agriculture in spraying depends on their productivity, ie the amount of work performed per unit time (ha / h). Productivity is one of the most important technical and operational indicators, which depends on the working width of the drone spray band, working speed, tank volume (technological capacity), the coefficient of use of change time in the operation of the sprayer drone (K), operator qualifications and crew organization.

Thus, the study of the productivity and justification of the effective operation of DJI agro drones Agras (T16, T20, T30) on the spraying of cultivated plants with plant protection products against pests and diseases is an urgent task.

The information obtained on the "real" productivity of Agras will allow prospective buyers to assess the potential of each of the models and choose the one for their farm that will allow them to qualitatively and in a short time to perform tasks in pest, disease and weed control.

3. Analysis of last researches and publications

The debut of DJI's agricultural helicopters began in 2015 with the Agras MG-1 model. In seven years, relatively short period of time, DJI agricultural helicopters have come a long way in evolutionary development to the latest flagship Agras T30, which automates, simplifies and speeds up many processes in fields and orchards.

In 2019, the Agras T16 model (Fig. 1) appeared, which was 67% more efficient than the previous MG-1 model, owing to a 60% increase in tank capacity, battery capacity and spray system capacity. The capabilities of T16 have expanded owing to the function of spraying orchards. T16 learned to fly pre-planned routes, flying over trees at planned points.

The Agras T20 helicopter (2020 model) managed to raise the efficiency bar by another 20%, to 12 hectares per hour. All owing to the increased to 20 l tank and expansion of a spray strip to 7 m. T20 (fig. 1) received system of scattering of firm fertilizers and seeds which is capable to cope with the set tasks 70 times faster than the person.

At the beginning of July 2021, DJI's flagship model Agras T30 appeared in Ukraine (Fig. 1). The new T30 model differs from its predecessors both externally and functionally. It became the best in all the main parameters: the number of nozzles doubled, the width of the spray strip increased to 9 m, the distance of communication with the remote control increased to 5 km. The efficiency of the model with a 30-liter tank increased to 16 hectares per hour. Compared to the T16 and T20 models, the T30 rechargeable batteries have a larger capacity and higher charging speed. The warranty period of the battery increased to 1000 cycles.

T16 T20 T30

Fig. 1. General view of Agras sprayers

A sufficient number of scientific works are devoted to the use of UAVs (drones) in agriculture, activities and management of agricultural enterprises. For example, works [1, 2] are devoted to the issues of ensuring the innovation process with the use of UAVs in the field of crop production, features of their use in agricultural production [3, 4, 5, 6, 7], remote monitoring [8, 9 , 10], spraying with plant protection products against pests and diseases [11, 12, 13, 14], productivity of their use [15, 16, 17] and economic feasibility [18, 19].

4. Aim of the researches

The aim of the paper is to study the effectiveness of DJI's Agras drones in spraying cultivated plants with pesticides, diseases, weeds and to establish their design and operating features.

5. Results of the researches

Before investigating the effectiveness of Agras UAVs on spraying crops with pesticides, diseases and weeds, we compare their technical and operational performance and establish design and operating features of the following models: Agras T16, T20 and T30.

Comparing the technical and operational indicators (Table 1) of Agras helicopters, we observe an improvement in almost all indicators with each of the following models: tank volume and as a result the maximum takeoff weight, spray bandwidth, etc. This is primarily due to DJI's desire to increase their productivity and efficiency.

All three models T16, T20 and T30 effectively spray crops due to powerful software, artificial intelligence and 3D operations planning. They contain a modular design of the aircraft, which contributes to the convenient maintenance of the system and increase flight safety. Their modular design simplifies assembly, especially the T30, and daily drone care. The light and strong platform is partly made of carbon fiber, which in folded form is 25% of the original size, which is convenient for their transportation. As for the T30 model, it is a helicopter with solid elements that are firmly attached to the frame, which avoids the problems with paws that were typical for previous models during landing.

Precise positioning of all Agras models is implemented by emitting GPS navigation radio signals in the L1 frequency range (1575.42 MHz), GLONASS navigation system in the L1 frequency range (1600.995 MHz) and Galileo - E1 (1575.42 MHz). If you use the RTK (Real Time Kinematic) service, you can obtain corrections to the measurements and set the location with centimeter accuracy in real time using the GNSS receiver in the network of permanent reference GNSS stations. The following operating frequencies are used in RTK mode: GPS L1/L2, GLONASS F1/F2, BeiDou B1/B2, Galileo E1/E5 [20, 21, 22].

Table 1

Technical and operational performance of Agras drones

Indicator	Agras T16	Agras T20	Agras T30
Tank volume, l	16	20	30
Maximum take-off weight, kg	42	47,5	66,5 (spraying) 78 (scattering)
Flight duration (maximum and minimum load), min	10-18	10-15	7,8-20,5
Number of nozzles	8	8	16
Spray bandwidth, m	4-6,5	4-7	4-9
Range of a signal of the remote control, km	3	3	5
Work efficiency, ha/h	10	12	16

On the previous T20 model, the dry fertilizer tank had a capacity of 20 liters. And on the T30, the tank volume is 40 kg, which allows you to process a larger area in essentially the same time.

Agras T30 has more injectors from which to pour. If on previous versions of T16 and T20 there were 8 of them, there are already 16 now. In addition, the location of the injectors has been changed: in T16 and T20 they were placed only on 4 beams, and in T30 - on all 6 beams. Also on the central rays – there are not 2 nozzles, but 4 [22].

Unlike the T16 and T20 models, the new T30 already has two cameras that transmit information both front and rear. This allows the operator to see what is happening to the helicopter during the flight.

The Agras radar system is able to determine operating conditions both day and night without exposure to light or dust. The level of flight safety has increased owing to the collision avoidance function at the front and rear of the aircraft. The innovative radar system is equipped with digital beamforming technology that supports 3D models (DBF technology) created from point clouds. Agras T30 clearly identifies obstacles - trees, supports, power lines - and then in the work accurately bypasses them.

The expected solution is that in the new model T30 manufacturers have resolved the issue of processing the edges of the field, which the previous models T16 and T20 didn`t have. In Agras T30 there is a function of overflight on a contour (upon processing of the main array). Sparaying Drone flies around the perimeter and processes plants (width of processing when performing work on the perimeter is 4 m). Quite often this function is used by agronomists.

For efficient operation of the T30 in the field for 10-12 hours three batteries are needed, although the manufacturer says that two are enough. This will avoid downtime due to waiting for charging.

The following Agras T30 operating modes are available for users for flights: "Route"; "A-B Route"; "Manual" (manual control); "Manual Plus". In more detail, the possible modes of operation of Agras T30 and their features can be found using [7, 22].

Agras intelligent mode independently develops the optimal route for each operation, and the software allows you to determine at which point of flight the working fluid in the tank will end. Moreover, the calculation is carried out under a specific rate of outflow. The volume of liquid in the tank is also determined automatically by a float type level meter (measurement error is about 80-120 ml) [22].

Unlike the T16 and T20 models, you need to create a field map to plan a "field planning" route by the Agras T30 drone itself or bypass the field on foot. This model does not provide the ability to measure the field with another monitoring drone (eg Phantom 4) and then flip the map to T30. Working on maps, such as Google Earth, is also not desirable, it is a work with a large error, which turns into underdevelopment along the contours.

Increasing the efficiency of sprayer drones means increasing their productivity and reducing specific time, battery and energy costs per unit of work performed.

Productivity of spraying drones is determined by the well-known dependence [23]:

$$W_h = 0{,}1 \cdot B_w \cdot V_w \cdot \tau, ha/h \qquad (1)$$

where B_w – working width of the drone`s spray band, m; V_w – working speed of the drone, km/h; τ – change time utilization factor.

Analyzing the dependence (1), we see that the productivity of the spraying drone depends on all the above components. Let's analyze each of them.

The working width of the boom sprayer (B_w) is determined by the width of the boom in expanded form and for modern self-propelled sprayers it is from 12 to 46 m. It is clear that increasing the width of the bar, increases the productivity of the unit, other things being equal

The working grip width of the spraying drone is determined by other conditions, namely: the diameter of the swing of the rotors, which create a downward flow of air, the number of rotors and the height above the surface of the culture. The width of the spray band is determined by the drone when creating a mission on the control panel and can reach values from 4 to 9 m (table 1). The agrodron potential is best revealed at a height of 4 m above the crops [18]. However, it is necessary to monitor the optimal ratio of the following four parameters: spray bandwidth, altitude, pour rate and flight speed. Factors such as wind speed, direction and topography may also affect the width of the grip. Therefore, they must also be taken into account when planning a flight mission.

Analyzing the dependence of productivity (1), the operating speed (V_w) of the agrodron can be represented as a function of many arguments:

$$V_w = f(N, D, T) \tag{2}$$

where N – power of drone rotors in the optimal mode; D – parameter that limits the maximum speed according to the criterion of the allowable stresses in the structural elements of the drone under the action of dynamic forces; T – technological parameter of limiting the working speed of the drone.

The power of the drone rotors must provide maximum traction for transporting and applying the working solution. For example, the Agras T16 drone contains rotors with a motor power of 2400 W each, which provides a maximum thrust of each rotor of 13.5 kg. This allowed the use of a tank with a capacity of 16 liters. As for, for example, the T30 model, to ensure the insertion of the plants protecting tools with a tank capacity of 30 liters spraying drone is equipped with rotors with a capacity of 3600 W with a maximum thrust of each rotor of 18.7 kg [22]. Thus, the increase in the payload of the drone requires an increase in energy and, consequently, an increase in battery capacity.

The maximum allowable speed of spraying drones on the parameter T is limited by: the performance of the installed pumps, the capacity of the nozzles to ensure a given rate of discharge of the working drug; properties of substances of the tank mixture, etc. Thus, taking into account all the factors that may affect the operation of the drone on the spraying of working areas, its electronic system itself automatically offers the operator the maximum possible working speed of spraying (7 m/s) [20, 21, 22]. It is also known that Agras drones have a maximum flight speed of 10 m/s and have a maximum resistance to wind at a speed of 8 m/s.

Now we consider the last indicator as a function of productivity (1), namely, the utilization factor of change time (τ). Productivity of spraying drones, as well as field machine units, largely depends on the efficiency of use of work shift time. The balance of time of change has a significant number of components that characterize the unproductive costs of time, which should be reduced, and increase only one parameter - the time of net work BEFORE. The coefficient of use of the shift time, which is calculated as the ratio of the net operating time of the drone to the total operating time of the shift, is calculated using the method described in [7].

The change time utilization factor is defined as:

$$\tau = \frac{T_m}{T_{sh}} \tag{3}$$

where T_m – time of the main (clean) work (spraying), h; T_{sh} – duration of shift, for spraying operation T_{sh}= 6 hours.

The calculation of the time of the main (clean, effective) work is performed using the method of calculating the production line of plant protection on the example of the drone Agras T30. Thus, the time to perform the main work (spraying) per shift is determined by the formula:

$$T_m = t_m \cdot n_c, h \tag{4}$$

where t_m – duration of working stroke of spraying drone for one cycle, h; n_c – the number of cycles of the drone per shift

$$n_c = \frac{T_{sh} - (T_{pf} + T_{tm} + T_r)}{t_c}, \tag{5}$$

where T_{pf} – duration of preparatory and final works, hours. Here T_{pf} = 0.4-0.6 hours; T_{tm} – duration of technical and technological maintenance of the drone, hours. Here T_{tm} = 0.1-0.3 hours; T_r – time for rest and other needs, h. Here T_r = 0.4-0.7 hours; t_c – cycle duration, hours.

The above-mentioned components of the duration of change of T_{pf}, T_{tm}, and T_r are accepted on the basis of own time observations. Under certain conditions, they may take on slightly different meanings. The calculation also did not take into account travel time from the office of the company providing these services to the location of the farm or work site.

The duration of the cycle, in this case, is the time of complete emptying of the drone tank (30 l), which is determined as follows:

$$t_c = t_{wt} + t_{fil} + t_{mov} + t_m + t_x + t_{ch},\ h \qquad (6)$$

where t_{wt} – waiting time for refueling, h. Provides the duration of replacement of the battery and tank. The tank of the Agras T30 drone cannot be removed. Therefore, only the battery is replaced. t_{wt} is exactly 0.015 hours; t_{fil} – duration of filling (refueling) of the drone tank, h. For the most part, refueling is done manually (for models T16 and T20) when filling the working solution with 20 l canisters. The approximate duration of refueling 16-20 liter tank Agras T16, T20 is from 0.025 to 0.040 hours. It is recommended to fill the Agras T30 tank with the help of filling stations (supply 40-60 l/min). Here t_{fil} = 0,025 hours; t_{mov} – duration of take-off and movement of the drone with the working solution from the place of refueling to the first pass in the bend and without the working solution in the opposite direction and landing at the take-off point, h; t_m – duration of the working session (spraying) of the drone, h; t_x – duration of drone displacement (left or right) at the end of the session, h. t_{ch} – duration of the operator's check of the basic flight settings, h.

The duration of the movement t_{mov} is determined as follows. The take-off and landing time of the drone is approximately 30 seconds (0.0083 h), and the flight distance (left or right of the refueling point) to the first pass is chosen for efficient use of time and takes about 100-200 m. Thereby, the duration of the movement to the first pass of the drone is written in the form

$$t_{mov} = 2\left(t_{take} + \frac{10^{-3}L}{V_{tech}}\right),\ h \qquad (7)$$

where L – the weighted average distance of the drone to the first pass in the fold, m. Here L = 150 m; V_{tech} – average technical speed of the drone to the first pass in the unit, km/h. Here V_{tech} = 20 km/h.

Thereby

$$t_{mov} = 2\left(0,0083 + \frac{10^{-3}\cdot 150}{20}\right) = 0,0316\ \text{h.}$$

The duration of the drone's operating time (tank emptying time) is determined by the formula:

$$t_m = \frac{10^{-3} l_m}{V_{wr}},\ h \qquad (8)$$

where l_m – the length of the path (flight) that the drone flies between two consecutive refueling.

$$l_m = \frac{10^4 \cdot V_t}{B_{wr} \cdot H_{wor}},\ \text{m} \qquad (9)$$

where V_t – capacity of the drone tank, l; H_{wor} – working fluid consumption rate, l/ha. Here H_{wor} = 5 l/ha.

The working width of the spray band of a spraying drone can vary within the limits specified in table 1. However, its value should be taken based on a recommendations obtained experimentally [18]. For example, the potential of the spraying drone is best revealed at a height of 4 m above the crops at the optimal ratios of such parameters as: spray bandwidth, flight altitude, rate of pouring the working solution and flight speed. It has been experimentally established (for Agras T30) that for most farms the most working scheme is when the width of the spray strip is 7.5 m, the pour rate is 7 l/ha, and the height is 3 m.

Thereby:

$$l_m = \frac{10^4 \cdot 30}{7,5 \cdot 7} = 5714,\ \text{m.}$$

However, it should be noted that it is not always advisable to use the maximum calculated path length, as the working solution may end in the middle of the field or on the opposite side (in Agras models). Therefore, the operator must always estimate the size of the sections, the length of the working run on this section, the distance of idle spans of the drone and the battery charge. They also need to calculate the need for a working solution to fill the tank, as the software Agras T16, 20, 30 does not provide for this, unlike XAG P20 or P30.

We accept the working area (Fig. 2) with a constant run length of 1000 m. We believe that the spraying drone begins to spray from point *A*, constantly shifting to the right to point *B*. Thus, starting its flight from point *A*, it can perform 5 full passes (5714: 1000 = 5.7). However, the last 5th pass of the spraying drone will end on the opposite side of the work area, which will negatively affect the efficiency of its work. Therefore, in this case, there are two options for solving the problem. The first is to make only four flights to, thus cultivating 3 hectares and not fully using the battery charge; the second - to reduce the rate of application of the drug to 6.5 l/ha, having agreed in advance with the customer, which will allow to perform an even number of flights, namely 6 flights, thus processing 4.5 hectares. For further calculations of Agras T30 work we accept an even number of flights, namely six.

Thus, the duration of the working stroke of the spraying drone (tank emptying time) with a flight distance of 6000 m will be

$$t_m = \frac{10^{-3} \cdot 6000}{25} = 0,24, \text{ h.}$$

It is believed that during 0.24 hours (14.4 minutes) of the main work of the drone the battery power will be just enough to perform a given mission. If the 25 % battery charge is indicated, the current mission must be stopped immediately and the spraying drone must return to the take-off point. Therefore, the operator must monitor this. The duration of idling (offset to the left during the cycle) is determined by the following formula:

$$t_x = \frac{10^{-3} \cdot l_x \cdot n_x}{V_x}, \text{ h} \qquad (10)$$

where l_x – the length of one idle turn of the drone, m. It is equal to its width l_x = 7.5 m; n_x – the number of idle turns of the drone during the emptying of its tank. Here $n_x = n_w - 1$; n_w – the number of working flights per cycle; V_x – speed of the drone when moving it to the left on a given bend, km/h. Here $V_x \approx 5$ km/h.

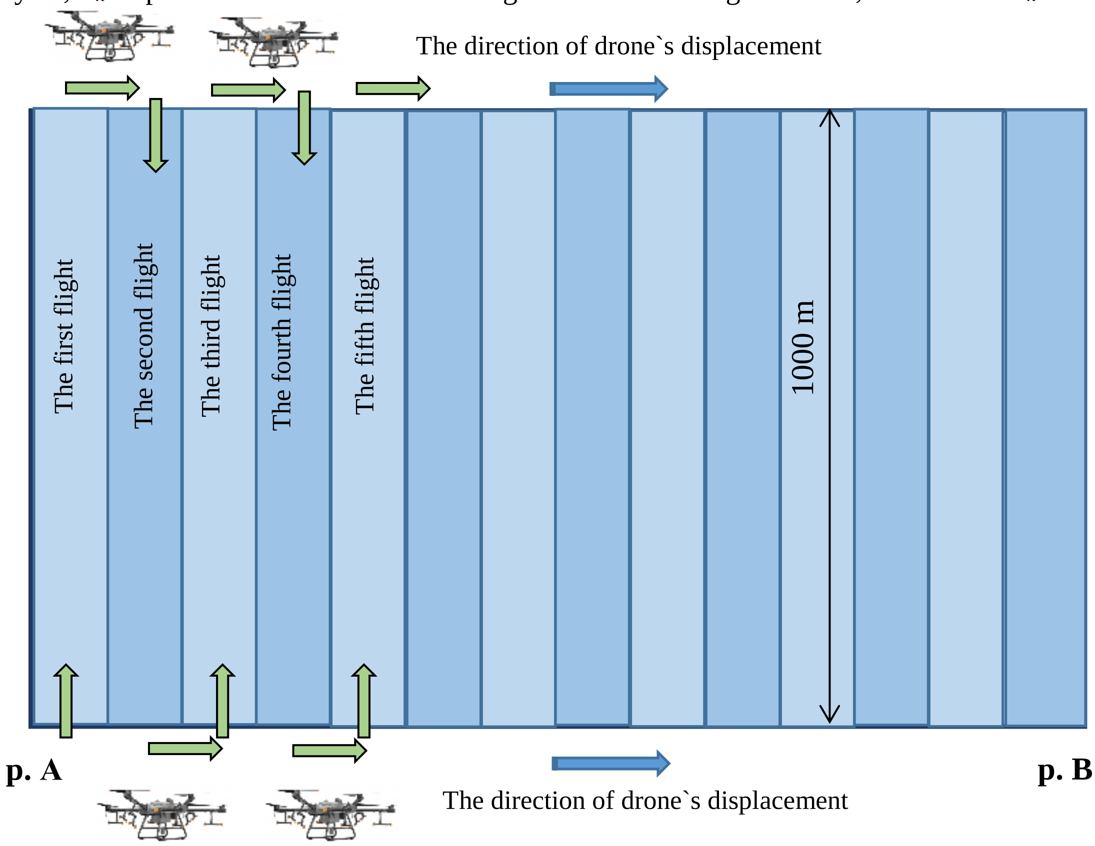


Fig. 2. Scheme of flight of the spraying drone

The number of working flights of the drone is determined by the dependence:

$$n_w = \frac{l_m}{l_w}, \qquad (11)$$

where l_w – working length of the field run, m. Under the accepted conditions l_w = 1000 m.
Thereby:

$$n_w = \frac{6000}{1000} = 6 \text{ repeats}, \text{ then } n_x = 6 - 1 = 5 \text{ repeats.}$$

The idle duration will be:

$$t_x = \frac{10^{-3} \cdot 7,5 \cdot 5}{5} = 0,0075, \text{ h.}$$

The duration of the operator's check of the basic flight settings t_{ch} is assumed to be zero (t_{ch} = 0 h), because they check them during the work of the operator's assistant (battery replacement, tank filling, etc.).

Therefore, the duration of the cycle, and in this case the time of complete emptying of the drone tank (30 l) will be:

$$t_c = 0{,}015 + 0{,}025 + 0{,}0316 + 0{,}24 + 0{,}0075 = 0{,}3191 \text{ h}.$$

Thereby the number of drone cycles per shift will be equal to

$$n_c = \frac{6-(0{,}5+0{,}2+0{,}6)}{0{,}3191} \approx 14 \text{ } cycles.$$

The main operating time of the drone per shift will be

$$T_m = 0{,}24 \cdot 14 = 3{,}36, h.$$

The change time utilization factor will be

$$\tau = \frac{3{,}36}{6} = 0{,}56.$$

Therefore, the productivity of the Agras T30 per hour of variable time will be

$$W_h = 0{,}1 \cdot 7{,}5 \cdot 25 \cdot 0{,}56 = 10{,}5, \ ha/\text{h}.$$

Such productivity of spraying drones is obtained on the fields of incorrect configuration and those that contain a significant number of obstacles, such as power lines.

Similarly, we perform the calculation of productivity of spraying drones Agras T16 and T20. The results of the calculations are shown in table 2.

Table 2

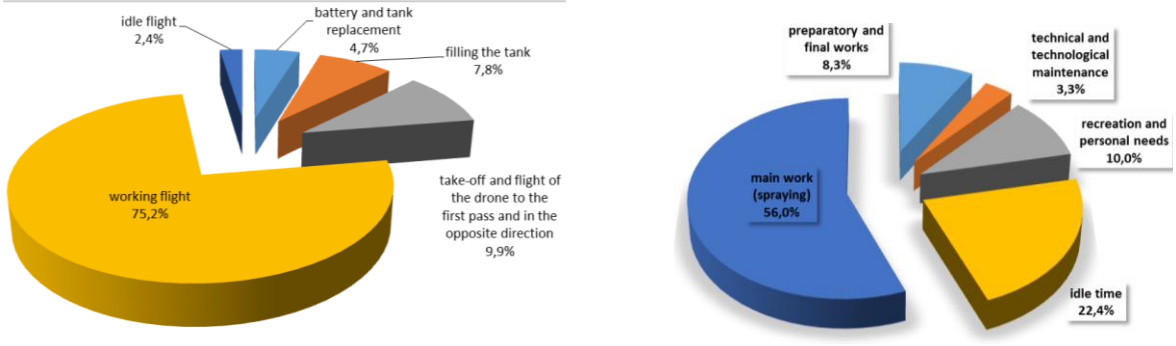
Productivity of Agras sprayer drones with the length of the run of 1000 m

Indicators	**Agras T16**	**Agras T20**	**Agras T30**
Working width of a spray strip, B_{wr}, m	6,0	6,5	7,5
Drone operating speed, V_{wr}, km/h (max)		25	
Consumption rate of working fluid, H_{wor}, l/ha	5,0	6,0	6,5
The flight distance of the drone to the complete emptying of the tank, l_m, m	5333	5128	6154
Duration of the drone's operation, t_m, h	0,16	0,16	0,24
Duration of idle displacements of the drone, t_x, h	0,0036	0,0039	0,0075
Duration of one flight cycle, t_c, h	0,2452	0,2448	0,3191
Number of cycles per shift, n_c	19	19	14
Duration of the main work per shift, T_m, h	3,04	3,04	3,36
Change time utilization factor, τ	0,51	0,51	0,56
Productivity of the spraying drone, W_h, ha/hour	7,65	8,29	10,5

The calculation of the performance of the spraying drones T16 and T20 is performed under the conditions recommended by [18], which were obtained experimentally. So, for the spraying drone Agras T16 we accept the working scheme: width of a strip of spraying of 6,0 m, norm of outflow - 5 l/ha, height - 3 m; for T20 - the width of the spray strip is 6.5 m, the pour rate is 6 l/ha, and the height is also 3 m.

Under the accepted conditions, the flight distance that the drone flies until the tank is completely empty is 5333 m for Agras T16 and 5128 m for Agras T20. As you can see, T16 and T20 can make a full 5 flights. However, after one mission they will need to perform one idle flight of 1000 m to return to the starting point. For further calculations we accept only 4 working spans (Table 2). Therefore, under such conditions, T16 and T20 drones will be able to perform 19 cycles during the shift, their duration of the main work per shift will be 3.04 hours, and the utilization factor of the shift time will be 0.51. Productivity of the spraying drones Agras T16 and T20 is 7.65 and 8.29 ha/h, respectively.

Figure 3 shows the distribution of the duration of one cycle of the Agras T30 drone and the balance of time change in percentage.



a *b*

Fig. 3. Distribution of duration of one cycle of operation (a) of the Agras T30 drone and balance of change time (b) in percentage

Analyzing the balance of change time of the drone Agras T30 as a percentage, we see that about 23 % is due to downtime of irregular time, which is caused by technical malfunctions, organizational problems and weather conditions.

Table 3 presents the results of the calculation of productivity of the spraying drones Agras T16, T20 and T30 in the field with a run length of 750 m.

Table 3

Productivity of Agras spraying drones with a run length of 750 m

Indicators	Agras T16	Agras T20	Agras T30
Working width of a spray strip, B_{wr}, m	6,0	6,5	7,5
Drone operating speed, V_{wr}, km/h (max)		25	
Consumption rate of working fluid, H_{wor}, l/ha	5,0	6,0	6,5
The flight distance of the drone to the complete emptying of the tank, l_m, m	5333	5128	6154
Duration of the drone's operation, t_m, h	0,24	0,24	0,32
Duration of idle displacements of the drone, t_x, h	0,006	0,0065	0,0105
Duration of one flight cycle, t_c, h	0,3276	0,3281	0,4021
Number of cycles per shift, n_c	14	14	11
Duration of the main work per shift, T_m, h	3,36	3,36	3,52
Change time utilization factor, τ	0,56	0,56	0,59
Productivity of the spraying drone, W_h, ha/hour	8,40	9,10	11,06

As we can see, the productivity of all Agras for plant protection has increased from 1000 m to 750 m when reducing the length of the run. This is primarily due to the increase in the number of working flights to and, consequently, the increase in the duration of the working flight of the drone in one cycle. In particular, the productivity of T16 and T20 drones increased by almost 10 %, and T30 drones - only by 5.3 %.

Due to the fact that the productivity of the drone depends primarily on the performance of the drone rotors and the capacity of the batteries, the selected mode of operation of the drone, the organization of work, the most important reserves for improving the productivity of the spraying drones are:

- maintenance of the high level of realization and use of power (traction) of helicopter motors throughout the entire exploitation process due to timely and proper maintenance of drones with the use of diagnostic tools, timely troubleshooting, appropriate adjustments, calibration, etc.;
- rational choice of operation mode of the spraying drone, width of capture, choice of the best speed mode at mission planning;
- increasing the utilization of shift time by better organization of spraying drones`work and their group work, introduction of rational flight methods for these conditions of the helicopter, improving the

working conditions of the drone (division of the field into units, if necessary, optimal width; choosing a rational number idle drone flights);

- early timely preparation of the spraying drones` flight missions, taking into account the peculiarities of the terrain, possible power lines and other third-party objects;
- organization, if necessary, of group work of the spraying drones to ensure the flow of production methods and improve their technological maintenance;
- application of optimal logistics, which would ensure timely control and accounting of compliance with variable standards, elimination of downtime and complete elimination of unproductive time spent when spraying plant protection products to control pests and diseases.

6. Conclusions

1. When comparing the technical means used for spraying crops from diseases, pests and weeds, the indisputable expediency of the use of unmanned aerial vehicles has been noted, which allows to solve the problem of trampling crops by 100%, damage to plants by sprayer rods, lack of soil compaction, ability to work immediately after rain, etc.

2. The analysis of technical and operational performance of the spraying drones Agras T16, T20 and T30 from DJI allows us to assert the dynamics in improving the efficiency of their use. Thus, the volume of the drone tank increased from 16 liters to 30 liters, the width of the spray fluid increased from 6.5 m to 9 m, increased efficiency (theoretical productivity) from 10 to 16 ha/h. The new agricultural spraying drone Agras T30 differs both externally and functionally. Among the main differences of the model are: the presence of two pumps with a capacity of 8 l/min; updated beam mounting; the presence of two surveillance cameras that transmit information both in front and behind the flight of the drone; the ability to process only the edges of the field; increased battery life (1000 charge cycles) and higher charging speed, etc.

3. It is noted that the performance of spraying drones depends on the diameter of the swing of the rotors, which create a downward flow of air, the number of rotors and the height above the crop surface. Their maximum permissible speed is limited by the performance of the installed pumps, the capacity of the nozzles to ensure a given rate of discharge of the working drug; properties of substances of the tank mixture, etc. It is noted that the balance of time to change the operation of the drone contains a large number of components that characterize the unproductive cost of time and which should be reduced, but only one parameter should be increased - the time of net work. Thus, analyzing the balance of time of change of the Agras T30 drone in percentage terms, we see that about 23 % is due to downtime of irregular time, which is caused by technical malfunctions, organizational problems and weather conditions.

4. When calculating the productivity of the spraying drones Agras T16, T20 and T30 at a run length of 1000 m we received, respectively, 7.65; 8.29 and 10.5 ha/h. The utilization rate of change time was 0.51 for T16 and T20, and 0.56 for T30. With the reduction of the run length to 750 m, the productivity of all Agras T16, T20 and T30 increased, respectively 8.40; 9.10 and 11.06 ha/h. This is due to the increase in the number of working flies of the sptaying drones and, as a consequence, increase the duration of the working flight of the drone in one cycle. In particular, the productivity of the spraying drones T16 and T20 increased by almost 10 %, and T30 drones - only by 5.3 %.

5. It is noted that the main reserves for increasing the productivity of the spraying drones are maintenance throughout the process of operation of the drone in working order due to timely and proper mantained maintenance of drones with the use of diagnostic tools; rational choice of operation mode of the spraying drone; increasing the utilization rate of shift time by better organization of spraying drones` work and their group work, the introduction of rational flight methods for these conditions of the spraying drones; early timely preparation of pre-flight missions, taking into account the peculiarities of the terrain; application of optimal logistics, which would ensure timely control and accounting of variables, elimination of downtime and complete elimination of unproductive time spent when spraying plant protection products to control pests and diseases.

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ЕФЕКТИВНІСТЬ ВИКОРИСТАННЯ ДРОНІВ AGRAS НА ОБПРИСКУВАННІ ТА ЇХ КОНСТРУКТИВНО-ТЕХНОЛОГІЧНІ ОСОБЛИВОСТІ

Агротехнічні операції по обприскуванню сільськогосподарських культур від хвороб та шкідників є важливою частиною практично в будь-якій агротехнології. Вони складають істотну частину собівартості всієї агротехнології та як наслідок - собівартість кінцевої одержаної продукції. Застосування безпілотних літальних апаратів (БПЛА) в сільському господарстві має величезний потенціал і з кожним роком інтерес до їх використання зростає в першу чергу при реалізації завдань точного землеробства.

Об'єктом дослідження у даній статті був процес обприскування робочих ділянок безпілотними літальними апаратами Agras.

Метою роботи є дослідження ефективності роботи дронів Agras компанії DJI на обприскуванні культурних рослин засобами захисту від шкідників, хвороб, бур'янів та встановлення їх конструктивно-режимних особливостей роботи.

Завданням роботи передбачалось: встановити конструкційно-режимні особливості безпілотно літальних апаратів Agras T16, T20 і T30; з'ясувати їх продуктивність на обприскуванні культурних ділянок та обґрунтувати можливі резерви у підвищенні продуктивності дронів-обприскувачів.

Методика досліджень ґрунтувалась на методі пізнавальної діяльності, математичне моделювання, методах аналізу та синтезу як інформації з офіційних джерел, так й інформації з праць інших дослідників.

У науковій роботі розглянуто відмінні техніко-експлуатаційні особливості гексакоптерів Agras T16, T20 і T30. Виконаний аналіз дозволяє стверджувати про динаміку в підвищенні ефективності їх використання. Обґрунтовані практичні аспекти їх використання при обприскуванні засобами захисту рослин, вибір необхідного режиму експлуатації.

Відмічено, що продуктивність дронів-обприскувачів залежить від діаметру розмаху роторів, які створюють низхідний потік повітря, кількості роторів та висотою над поверхнею культури. Їх максимально допустима швидкість обмежена продуктивністю встановленими насосами, пропускною здатністю форсунок для забезпечення заданої норми виливу робочого препарату; властивостями речовин бакової суміші тощо.

Наведено розрахунок експлуатаційної продуктивності ДО Agras T16, T20 і T30 при довжині гонів ділянок 750 і 1000 м. Продуктивності ДО Agras T16, T20 і T30 при довжині гону 1000 м одержали відповідно 7,65; 8,29 і 10,5 га/год. При зменшенні довжини гону до 750 м продуктивність усіх ДО Agras T16, T20 і T30 зросла, відповідно 8,40; 9,10 і 11,06 га/год. Встановлено, аналізуючи баланс часу зміни роботи дронів Agras у відсотковому співвідношенні, що близько 25 % припадає на простої ненормованого часу, які спричинені через технічні несправності, організаційні неполадки та погодні умови. Відмічені найважливіші резерви у підвищенні продуктивності дронів Agras компанії DJI на обприскуванні культурних рослин засобами захисту від шкідників, хвороб і бур'янів.

Ключові слова: *безпілотний літальний апарат, гексакоптер, Agras, дрон-обприскувач, обприскування, планування польотів, коефіцієнт використання часу зміни, баланс часу зміни, продуктивність дрона.*

Ф. 11. Рис. 3. Табл. 3. Літ. 23.

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