STUDY OF UNIT ENERGY PARAMETERS TILLING SOIL WITH HARROW USING SCREW WORKING BODIES

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Abstract. The article presents the technical specifications of the harrow and a general view of the unit for surface soil cultivation using screw-type working bodies, and outlines theoretical and experimental studies on determining the qualitative and energy parameters of soil cultivation. Based on the studies conducted, corresponding regression equations and response surfaces were constructed to investigate the influence of tillage depth, the angle of attack of the screw working body and the machine travel speed on fuel consumption. Analysis of the regression equation shows that the dominant factor influencing fuel consumption is the soil tillage depth h. The angle of attack of the screw working body β also has a significant influence on fuel consumption. The least influential factor is the machine travel speed V.

Keywords: harrow, screw working body, soil working depth, angle of attack, machine travel speed, fuel consumption.

Introduction

A harrow has been developed based on the interaction of soil particles with helical surfaces, the working element of which is a helical surface (helix). To balance the torque, the harrow must be configured with two helical working elements. The surface of the second working element must have a helical surface with the opposite direction of winding and straight generatrixes.

This working element operates similarly to disc implements. At the moment of contact between the helical blade and the field surface, there are angles analogous to the angles of attack and roll as for discs. The roll angle can be adjusted by changing the inclination of the straight generatrixes of the helical surface relative to its axis. A harrow with helical working elements creates an optimal soil structure by shearing, rolling and crushing the soil clods with the helical surfaces. The harrow parameters ensure high-quality levelling, intensive crumbling and mixing of the soil with crop residues, by adjusting the working depth as the speed and angle of attack of the working elements change.

Studies on harrows with helical tines have been presented in numerous publications. In particular, research in the agronomic indicators of soil tillage quality using harrows with helical tines is presented in [1], the influence of design and technological parameters of the developed variants of harrows with helical working bodies on the efficiency of incorporating plant residues is presented in [2], a study of the performance indicators of harrows with helical working bodies, namely the determination of deviation from the specified soil tillage depth and an investigation of the furrow bottom, is presented in [3]; a study of the traction resistance of a harrow with screw-type working bodies is presented in [4]; theoretical studies of the movement of soil particles along a screw surface are presented in [5; 6].

Unfortunately, however, there are currently no studies dedicated to the behaviour of machine-tractor units that include screw harrows. It should be noted, however, that theoretical studies on the dynamics of such units are presented in [7; 8]. Using the methodology described in these works, it may be possible to conduct similar studies in the future. It should also be noted that screw harrows are capable of significantly pulverizing the soil and separating large soil particles from small ones. By applying the fundamental principles outlined in [9], it is possible to conduct similar studies that will significantly improve the quality of harrowing.

For a more comprehensive study of the energy characteristics of a harrow with a screw-type soil-working element, it is relevant to conduct a study to determine the tractor fuel consumption during soil cultivation using a machine-tractor unit comprising a harrow with screw-type working elements.

Materials and methods

For the experimental studies, a harrow with helical working bodies was used, the diagram of which is shown in Fig. 1.

The harrow with helical working bodies (Fig. 1) [10] consists of a frame 1 with an automatic coupling 2, soil-tilling units with helical working bodies 3, comprising a frame 4, on top of which the coils of the helical working body 5 are secured, and the frame comprises two discs 6, to which are attached bearing supports 7 with a threaded shaft 8 and nuts 9, which are connected to one another by means of six rods 10, symmetrically attached around the periphery of the discs 6 at equal distances, guides 11 and 12, clamps 13 with fasteners 14 (angle of attack fixing device), and battery frames 15 with an axle 16.

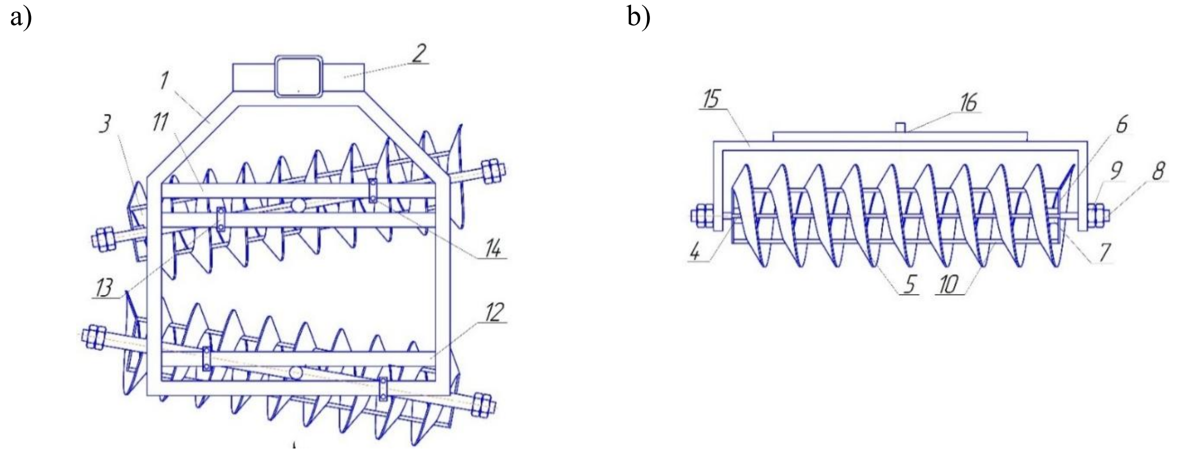

Fig. 1. **Diagram of a harrow with screw-type working bodies (a) and diagram of a battery of screw-type working bodies (b)**

The harrow is mounted on the tractor via a drawbar 2. The working width and angle of attack of the harrow are adjusted by loosening the fasteners 14; the bolted connection on the clamps 13 and the soil-working battery 3 hang on the axle 16 in the guides 11 (or 12). Both tillage units 3 are moved along the guide 11 (or 12) to the required position; for example, for 'track-to-track' operation, the angle of attack is set to $0° < \alpha < 40°$ (depending on the soil structure). The clamps 13 are tightened using fasteners 14 and the soil-working units 3 are secured relative to the guides 11. The harrow with helical working bodies may be equipped with additional soil-working units having specific preset values for the angle of inclination of the helical surface of the working body (roll angle) and the height of the helical working body flange, depending on the physical and mechanical properties of the soil and the working depth. Table 1 presents the technical specifications of the experimental version of the harrow with helical working bodies.

Table 1

Technical specifications of the harrow with screw-type working bodies

Parameters	Values
Design working width, m	1.3
Tractor attachment	mounted
Weight, kg	272
Number of helix turns in the battery	5
External diameter of the coil, mm	562–570
Working depth, m	0.03-0.12
Operating speed, km·h^{-1}	4...17
Overall dimensions in transport ($L \times B \times H$), mm	2090 × 1430 × 1250

Fig. 2 shows a general view of the harrow with screw-type working bodies, while Fig. 2b shows the tractor-harrow combination comprising a JINMA 404E tractor and a harrow with screw-type working bodies, used to determine its performance indicators during soil cultivation.

The force characteristics of screw-type working bodies are determined by the soil resistance forces acting on the blade and the screw surface. The use of one type of working body design or another leads to the predominance of a particular type of deformation of the soil layer. Consequently, according to [4; 11], the soil resistance force, or the traction resistance of the working body in the direction of the MTA movement, will be determined via the specific soil resistance:

$$P_T = k \cdot A_n + \mu \cdot Q, \tag{1}$$

where k – specific soil resistance, k = 20-130, kPa [4; 11];
A_n – cross-sectional area of the soil layer, m^2;
μ – is the reduced coefficient of rolling friction;
Q – weight of the harrow with screw-type working bodies, kg.

a) b)

Fig. 2. **General view of a harrow with screw-type working bodies:** a – machine-tractor unit; b – JINMA 404 E tractor and harrow with screw-type working bodies

The general expression for determining the traction resistance of a harrow with screw-type working bodies is given by [4; 11]:

$$P_T = k \cdot n \cdot \left[R^2 \cdot \arccos\left(1 - \frac{a}{R}\right) - \left(R - a\right) \cdot \sqrt{2Ra - a^2} \right] \cdot \sin\alpha \cdot \left[1 + \tan\left(\gamma + \varphi\right)\right] + \mu \cdot Q, \tag{2}$$

where n – number of turns of the helical surface simultaneously embedded in the soil, according to the design features of the helical harrow section;
R – outer radius of the helical surface, m; a is the soil working depth, m;
γ – angle between the front working surface of the soil-working tool coil and the wall of the furrow, deg;
φ – angle of soil friction on the surface of the soil-working element coil, φ = 16.7 deg.

The angle of attack α can be expressed as: $\alpha = \varphi_R + \beta$, where φ_R is the angle of inclination of the helical surface of the soil-working implement, $\varphi_R = \arctan(h \cdot R^{-1})$, deg; β is the angle of the harrow section relative to the direction of travel of the machine, deg.

The main indicators of a vehicle traction performance and fuel efficiency are: traction power N_T, kW; traction force P_T, kN; speed V, km·h^{-1}; towing capacity δ, %; hourly fuel consumption G_T, land specific fuel consumption g, l·ha^{-1} [12]. Specific fuel consumption characterises the fuel efficiency of a vehicle operating in working gears depending on the tractive force and is a derivative of hourly fuel consumption and tractive power. Specific fuel consumption decreases as the load increases and becomes minimal at maximum power, whilst under overload, specific fuel consumption generally increases. Based on well-known expressions [13], specific fuel consumption can be determined using the formula:

$$g = \frac{G}{S} = \frac{W}{S \cdot q \cdot \gamma} = \frac{P_T \cdot l + W_{TP}}{L \cdot l \cdot q \cdot \gamma} = \frac{P_T}{L \cdot q \cdot \gamma} + \frac{W_{TP}}{S \cdot q \cdot \gamma}, \tag{3}$$

where g – specific fuel consumption of the machine-tractor unit, kg·ha^{-1}; G is fuel consumption, kg;
S – area worked, m^2;
W – energy expenditure for the operation of the machine-tractor unit, J;
q – calorific value of fuel, J·kg^{-1};
γ – fuel density, kg·m^3;
P_T – tractor tractive force, equal to the resistance force of the working unit, kN;
l – distance travelled by the machine-tractor unit, m;
L – working width of the working unit, m;
W_{TP} – energy expenditure required to generate the tractor tractive force, J.

Assuming that $W_{TR}\cdot(S\cdot q\cdot\gamma)^{-1}$ is approximately a constant value, it can be concluded that the key component of the specific fuel consumption is the tractive force of the tractor or the resistance force of the harrow with helical working bodies.

Thus, the specific fuel consumption can be expressed as:

$$g=\left\{k\cdot n\cdot\left[R^2\cdot\arccos\left(1-\frac{a}{R}\right)-\left(R-a\right)\cdot\sqrt{2Ra-a^2}\right]\cdot\sin\alpha\cdot\left[1+\tan\left(\gamma+\varphi\right)\right]+\mu\cdot Q\right\}\cdot\left(L\cdot q\cdot\gamma\right)^{-1}+\frac{W_{TP}}{S\cdot q\cdot\gamma}. \quad (4)$$

Equation (4) shows that the specific fuel consumption during operation of the unit for continuous soil cultivation depends mainly on the parameters of the working bodies. Soil parameters in these equations are reflected by the coefficient of soil friction against metal and the specific soil resistance.

Consequently, using equation (4), it is possible to determine the specific fuel consumption and, accordingly, the operational fuel consumption when the unit (JINMA 404 E tractor and harrow with helical working bodies) is operating for continuous soil cultivation.

The methodology for experimental studies to determine operational fuel consumption is as follows. For the study, we selected a uniform field plot measuring 130 m × 50 m, free of slopes, hills and valleys. The length of the run was divided into three sections: the first – a distance of 20 m for accelerating the unit and maintaining a steady operating mode; the second – the section under investigation, 100 m in length; the third – 10 m in length for breaking the unit. The first and third sections of the run were not included in the measurements. To ensure the validity of the experiment, the tractor-trailer combination started moving from the same side each time and maintained the same average speed for each series of experiments. After adjusting the tractor-trailer combination in accordance with the experimental design matrix, the combination started moving from one side of the test section. During the studies, the gear ratio and speed remained constant, and the time taken to traverse the test section and fuel consumption were recorded.

To determine fuel consumption, a portion-type fuel flow meter connected to the tractor's fuel system and 250 ml and 500 ml measuring cups were used [12].

The metered flow meter was connected to the tractor fuel system via three-way valves, in parallel with the fuel supply and return lines from the high-pressure fuel pump, such that during acceleration and braking of the unit, fuel was drawn from the tractor standard fuel supply system (from the main tank), whilst during the experiment, the three-way valves were switched and fuel from the metered flow meter was used. After the tractor was stopped, fuel was drained from the flow meter and the remainder was determined from the initial quantity of 500 ml.

Using the methodology for conducting a full-factorial experiment PFE-3^3 [14], experimental studies were carried out to determine the influence of the soil tillage depth h, the angle of attack of the screw working body β and the unit's travel speed V on the fuel consumption rate g (optimisation parameter) during soil tillage using a machine-tractor unit comprising a JINMA 404 E tractor and a harrow with screw-type working bodies, i.e. $g = f(V, \beta, h)$. To obtain the values of the variable under investigation, the peak (maximum) values obtained from the data analysis were used.

For each factor, the experiment was conducted at least three times, after which the mean value of the result was determined and used for further statistical analysis of the experimental results.

After coding the factors (Table 2), a design matrix for a 3^3 factorial experiment was drawn up for a number of trials $N = 3^3$.

Table 2

Results of factor coding and levels of variation in the study of tractor fuel consumption

Factors	Designation		Variation of variation	Levels of variation, natural/coded		
	Code	Natural				
Vehicle of the unit, V, km·h^{-1}	X_1	x_1	4	4/–1	8/0	12/+1
Angle of attack of the screw working element, β, deg	X_2	x_2	10	15/–1	25/0	35/+1
Soil cultivation depth, h, m	X_3	x_3	0.02	0.08/–1	0.1/0	0.12/+1

The experimental studies to determine the dependence of tractor fuel consumption and the processing of experimental data were carried out in accordance with standard methodology.

Results and discussion

The regression equation for determining the fuel consumption rate g, l·ha^{-1} of a tractor when tilling the soil using a tractor-implement combination comprising a JINMA 404 E tractor and a harrow with screw-type working parts, as a function of the combination's travel speed V, km·h^{-1}, the angle of attack β of the screw tine assembly, deg, and the tillage depth, h, m, i.e. $g = f(V, \beta, h)$, for real values of the factors takes the form:

$$g = 9.1874 - 0.0036 \cdot V + 0.0044 \cdot \beta + 6.9625 \cdot h + 0.3705 \cdot \beta \cdot h + 0.6025 \cdot V \cdot h + 132.75 \cdot h^2 . \quad (5)$$

The resulting regression equation (8) can be used to determine the tractor fuel consumption g when tilling with a machine-tractor unit within the following ranges of input factors:

$$4 \le V \le 12 \text{ (km·h}^{-1}\text{)}; \; 15 \le \beta \le 35 \text{ (deg)}; \; 0.08 \le h \le 0.12 \text{ (m)}.$$

Analysis of the regression equation shows that the factors exerting the greatest influence on the change in fuel consumption g are: the working depth h and the angle of attack β of the propeller blade assembly. In general, an increase in fuel consumption g is caused by all factors: h, β and V.

The statistical indicators of fuel consumption are as follows: mean value g_c = 12.7 l·ha^{-1}; variance D = 2.21(l·ha^{-1})^2; standard deviation σ = 1.489 l·ha^{-1}; coefficient of variation υ = 11.7%.

Values of indicators for conducting the study using the regression analysis method: calculated value of Fisher F-test, F_p = 0.4581 (table value F = 2.0558); calculated value of Cochran G-test, G_p = 0.1083 (table value G = 0.2353); multiple correlation coefficient, R = 0.9699; significance level, α = 0.05.

Using Statistica-6.0 software for PCs, we constructed a graphical representation of the intermediate general regression models in the form of quadratic response surfaces of the tractor fuel consumption g as a function of two variable factors $x_{i\,(1,2)}$ at a constant, unchanging the level of the corresponding third factor $x_{i(3)}$ = const. Graphical representations of the results showing the dependence of the tractor fuel consumption g, obtained using Statistica-6.0, are shown in Fig. 3.

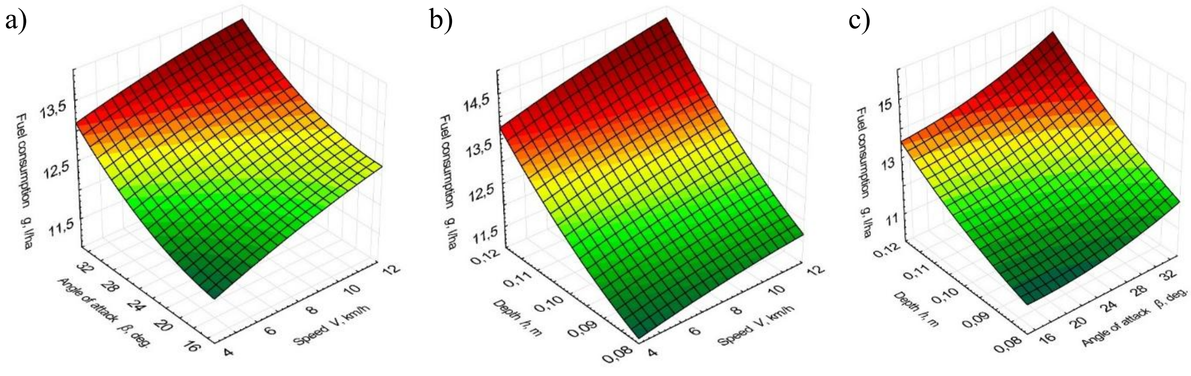

Fig. 3. **Tractor fuel consumption *g* during soil cultivation as a function of**: a – changes in the tractor's travel speed V and the angle of attack β of the working tools (h = 0.1 m); b – changes in the unit's travel speed V and the soil tillage depth h (β = 25 deg); c – changes in the angle of attack β of the row of helical working bodies and the soil cultivation depth h (V = 8 km·h^{-1})

The response curves (Fig. 3) show that as the factors of tillage depth h, the angle of attack β of the screw working body assembly and the harrow speed V (of the machine-tractor unit) increase, the tractor fuel consumption g rises, with the highest fuel consumption value being 15.4 $l \cdot ha^{-1}$ at maximum values of soil tillage depth h = 0.12 m and the angle of attack of the screw working body assembly β = 35 deg. The minimum value of the tractor fuel consumption g is 10.6 $l \cdot ha^{-1}$ at the minimum values of the soil tillage depth h = 0.08 m, angle of attack of the screw working body assembly β = 15 deg and the speed of the machine-tractor unit V = 4 $km \cdot h^{-1}$.

Analysis of the regression equation and response surfaces shows that the dominant factor influencing fuel consumption is the soil working depth h. The angle of attack of the working auger β also has a significant influence on fuel consumption. The least influential factor is the speed of the tractor-machine unit V.

A similar trend regarding the influence of the harrow design and technical parameters on its resistance force was identified in the study cited in [4], which presents the results of research on the traction resistance of a harrow equipped with helical tines.

The studies [15; 16] examined fuel consumption during soil cultivation with a rotary harrow and showed that the depth of cultivation has the greatest impact on tractor fuel consumption, while speed has a negligible effect, since increasing the machine travel speed reduces the duration of cultivation.

Additionally, studies [17-20] investigated the effect of tillage parameters on the productivity of a disc harrow and established that tillage depth and angles of the harrow discs significantly increase traction resistance and, consequently, fuel consumption. These findings confirm the validity of the research presented in this article.

Conclusions

1. This article presents the technical specifications of a harrow with screw working bodies and a general view of the machine-tractor unit for surface tillage using screw working bodies.
2. To determine the qualitative and energy parameters of soil cultivation using a harrow with helical tines, theoretical and experimental studies are presented on the influence of the cultivation depth, the angle of attack of the helical tine, and the machine forward speed on fuel consumption.
3. Analysis of the regression equation and response surfaces shows that the dominant factor influencing fuel consumption is the tillage depth h.
4. The angle of attack of the screw working element β also has a significant influence on fuel consumption.
5. The least influential factor is the speed of the machine-tractor unit V.

Author contributions

Conceptualization, V.B., O.G.; investigation, M.K., O.T. and S.P.; methodology, D.V., A.R.; validation, M.R.; data curation, M.C. All authors have read and agreed to the published version of the manuscript.

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