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MATHEMATICAL MODEL OF THE ENERGETIC CONSUMPTION FOR SOIL DIGGING MACHINES IN GREENHOUSES

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Abstract: *Preparing the germination bed in greenhouses can be done by several technologies, most of them including soil digging with a special machine manufactured for this purpose. The main disadvantage of this machine refers to the relatively high energetic consumption, which increases the work cost. Starting from the working process executed by the machine, the total energetic consumption is decomposed in representative components, for which the energetic computation relations are given. Finally a complex and general relation of the energetic consumption is obtained, by which interesting processing optimization solutions are being offered for this important functional parameter, available for designers and manufactures but also for users.*

Key words: *greenhouses, mathematical model, soil digging machine.*

1. Introduction

Mathematical modeling of the energetic of soil digging machines in protected spaces means to establish the relations of calculation of the necessary energy components in ground processing and their analysis in order to find methods of reducing energy consumption in the work of preparing the seed-bed in greenhouses [1], [2], [4].

Based on the study of the energetic of the machinery on the work of preparing the germination bed in greenhouses, the total mechanical energy components for each of them were determined, which are shown in Figure 1.

Energy consumption in works of the soil, in general, are characterized by [3]: specific cutting surface of the soil S_{sp} and the specific mechanical work, L_s.

Specific surface for cutting the unit volume of the soil is the ratio of area and volume of the displaced soil in m^2/m^3.

Specific mechanical work is the work necessary for processing the deployment of the unit volume of soil, J/m^3 [5], [6].

2. Material and Method

Energy consumed during soil processing with soil digging machine, E_{tms}, is used for the movement of the working machine, for cutting and deployment of soil slices, for throwing the deployed slices, for self pushing and for covering the loss from the transmission of the machine, is:

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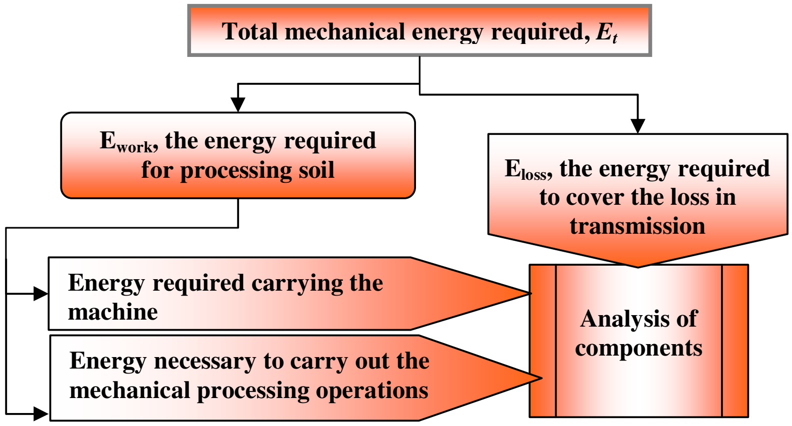

Fig. 1. *Methodology of the study and mathematical modeling of total mechanical energy*

$$E_{tms} = E_{movement} + E_{cut} + E_{trow} + E_{push} + E_{loss} \ \text{[J]}. \quad (1)$$

Starting from equation (1), the total energy required to drive machinery to dig the soil with plain working component is calculated with:

$$E_{tms} = f \cdot G_{ms} \cdot v_m \cdot t_{ms} + \frac{\mu \cdot \rho \cdot g \cdot a^2 \cdot b}{\sin\psi \cdot \cos\psi} \cdot z \cdot \frac{\varpi \cdot t_{ms}}{2\pi} \cdot v_m \cdot t_{ms} + \frac{B \cdot a \cdot \rho \cdot v_m \cdot v_x^2}{2} \cdot t_{ms} + \\ + \frac{2\pi}{\varpi} \cdot a \cdot B \cdot \rho \cdot g \cdot \text{tg}\,\psi \cdot v_m^2 \cdot t_{ms} + E_{loss} \ \text{[J]}, \quad (2)$$

where: f is the coefficient of tire rolling resistance between the soil and the machine; G_{ms} - weight of the machine, [N]; v_m - machine speed, [m/s]; t_{ms} - time of digging, [s]; μ - friction coefficient between the soil and spade; ρ - soil volumetric weight, [N/m^3]; *a, b* - excavated soil slice size, [m]; ψ - angle of attack of the spade, [°]; z - number of spades; ω - angular speed of the crankshaft, [rad/s]; B - working width of the machine, [m]; v_x - component of the relative speed to the direction of advance of the machine, [m/s], [7].

In equation (2) are some elements for which there is insufficient data, such as the angle of attack of the spade ψ; forward direction component of velocity of a spade, v_x. This data is established by theoretical calculations and graphical determinations.

For the theoretical study of the angle of attack a mathematical model is built achieving:

$$\psi = 2\pi - \theta_2 - \alpha = \varphi_2(\theta_1) - \varphi_1(\theta_1) - \alpha = \\ = \arccos\frac{r_1^2 + r_2^2 - r_3^2 + r_4^2 - 2r_1r_4\cos\theta_1}{2r_2\sqrt{r_1^2 + r_4^2 - 2r_1r_4\cos\theta_1}} - \text{arctg}\frac{-r_1\sin\theta_1}{r_4 - r_1\cos\theta_1} - \alpha \ [^\circ], \quad (3)$$

where: θ_1 is the angle of the rotation of the leading element of the quadrilateral mechanism of the digging machine; θ_2 - angle of rotation of the driven element; α - constant angle from the built; φ_1, φ_2 - angles dependent on the angle θ_1; r_1, r_2, r_3, r_4 - rectangle side length mechanism.

Angle of attack of the spade during work time varies as the angle of rotation of the crankshaft is also variable in time according to the relation: $\theta_1 = \varpi\, t$.

The medium value of the angle of attack is determined graphically for the specific case of soil digging machine MSS-1, 40. Dimensions of the rectangular mechanism of the machine MSS-1, 40 are: $r_1 = 0.17$ m; $r_2 = 0.35$ m; $r_3 = 0.26$ m; $r_4 = 0.40$ m, $\alpha = 8°$.

The variation of the angle of attack of the spade is shown in Figure 2. In determining the average component tg ψ during digging the determination of the rotation angle range in which the actual digging is made is necessary.

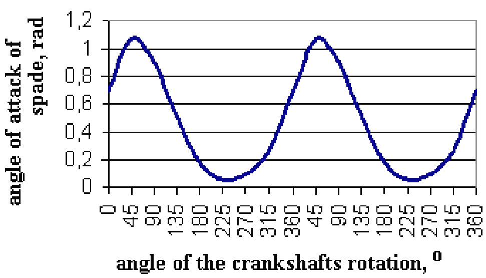

Fig. 2. *Variation of the spades angle of attack depending on the angle of the crankshafts rotation*

Figure 3 shows the trajectory of the top of the spade and determines this interval graphically. From the graphics presented we can see that the range of crankshaft rotation angle in which the digging is executed is between 225°...405° + *T*, *T* being the period of motion, which in this case is 360°. Thus, while digging tg ψ average is equal to:

$$\text{tg}\,\psi_{med} = 0.62.$$

The medium value of $\sin\psi \cdot \cos\psi$ is considered:

$$\sin\psi_{med} \cdot \cos\psi_{med} = 0.45.$$

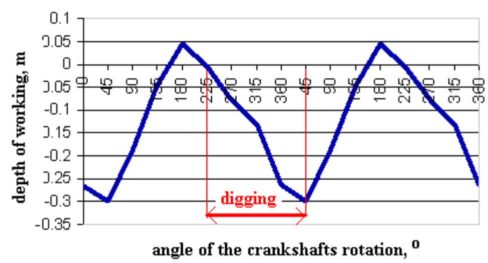

Fig. 3. *Trajectory of the top of the spade*

Substituting the average values of components, determined graphically, the relationship of total energy consumption of the work of the soil with the digging machine, one gets:

$$E_{tms} = f \cdot G_{ms} \cdot v_m \cdot t_{ms} + \frac{\mu \cdot \rho \cdot g \cdot a^2 \cdot b}{0.45} \cdot z \cdot \frac{\varpi \cdot t_{ms}}{2\pi} \cdot v_m \cdot t_{ms} + \frac{B \cdot a \cdot \rho \cdot v_m \cdot (-4.37)^2}{2} \cdot t_{ms} + 0.62 \cdot \frac{2\pi}{\varpi} \cdot a \cdot B \cdot \rho \cdot g \cdot v_m^2 \cdot t_{ms} + E_{loss} \text{ [J]}. \quad (5)$$

Mathematical model of energy consumption of the work of the soil with the digging machine, expressed by equation (5), provides information necessary to optimize machine parameters to minimize its energy consumption.

Energy necessary for the movement of the soil digging machine, $\boldsymbol{E_{movement}}$, is transformed into mechanical work necessary for the movement of the machine and in mechanical work of deformation of the soil and of the transport wheels. G_{ms} is directly proportional to the weight of the machine and rolling resistance coefficient *f* between the transportation wheel and soil:

$$E_{movement} = f(f, G_{ms}).$$

Reducing energy consumption for hauling the soil digging machine is to reduce these two elements.

Weight reduction of the machine starting from the design and construction phase may be obtained by using lighter materials, but adequate in terms of resistance to mechanical stress.

The component of forward motion of the speed of the spade v_x is determined graphically for the case β = 0°. The variation of the component of the speed of spade on the motion direction v_x is shown in Figure 4.

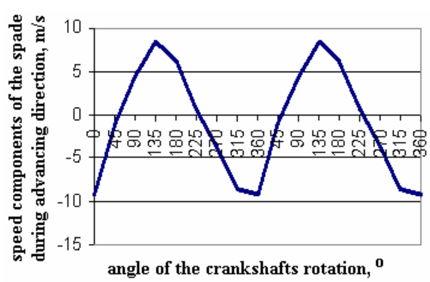

Fig. 4. *Variation of the speed components of the spade during advancing direction*

From the chart presented results that the average speed of the spade during digging is equal to:

$$v_x = -4.37 \text{ [m/s]}.$$

Reducing rolling resistance coefficient can be provided by using wheels with diameters and widths as high as possible, with low tire pressure.

Mechanical energy necessary to carry out operations, E_{cut} and E_{trow} is used to cut, deployment and disposal of soil slice.

Energy required to cut and slice the soil displacement depends on the dimensions of the displacement of the soil, being directly proportional to the depth and width of the spade so the number of spades in the soil at a time and physical and mechanical properties of soil, namely:

$$E_{cut} = f(a^2, b, z, \mu, \rho).$$

The energy for throwing the slices deployed depends on the dimensions of the displaced soil and physical properties of the processed soil:

$$E_{throw} = f(a, B, \rho).$$

Reduction of the energy required by the mechanical spading operations may be achieved by reducing the chip size of the displaced soil by doing the work once the soil has optimum physical and mechanical properties in terms of work.

Energy consumed for self pushing, E_{push}, occurs due to friction between the spade and the soil. It is an inconvenience which manifests itself by converting mechanical energy of rotation received from the tractor P.T.O for self pushing. Energy consumed for this is directly proportional to the depth of work, width of the spade, forward speed, but inversely proportional to the rotational speed of the crankshaft:

$$E_{push} = f(a, b, \rho, v_m, 1/\omega).$$

It is indicated that forward speed be smaller than the component of the speed of the spade in the direction of advance, which is confirmed in the specific case studied.

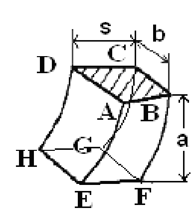

Fig. 5. *Slice dimensions of soil displaced by the digging machine*

Energy consumed by transmission loss due to friction occurring in machine mechanisms. The reduction of loss can be achieved by reducing the moving bodies and by reducing friction through lubrication.

Specific cutting surface is a geometrical parameter of the displaced soil slices [2]. It is the ratio of the cutting surface of the soil displaced and its volume:

$$S_{sp} = \frac{S_t}{V} \text{ [m}^2\text{/m}^3\text{]}, \quad (6)$$

where: S_t cut surface of the displaced soil, in m^2; V - volume of soil displacement in m^3.

The cut surface of the displaced soil is calculated from the geometry shown in Figure 5, such as:

$$S_t = S_{CBFG} + S_{EFGH} + 2 \cdot S_{ABFE} \approx \approx a \cdot b + b \cdot s + 2 \cdot a \cdot s \text{ [m}^2\text{]}, \quad (7)$$

where notations correspond to those in Figure 5 and have the following meanings: a working depth in m; b - thickness of the slice at the surface of the soil, in m; s - the step of the machine in m.

Step of the machine is calculated:

$$s = v_m \cdot \frac{2\pi}{\varpi} \text{ [m]}. \quad (8)$$

Dislocated soil volume by a spade can be considered equal with:

$$V = s \cdot a \cdot b \text{ [m}^3\text{]}. \quad (9)$$

Substituting relations (7) and (9) in the formula of the specific cutting surface formula is obtained:

$$S_{stms} = \frac{\omega}{2\pi \cdot v_m} + \frac{1}{a} + \frac{2}{b} \text{ [m}^2\text{/m}^3\text{]}. \quad (10)$$

Cutting surface area is inversely proportional to increasing working depth, which is observed from the diagram drawn for the concrete conditions of work, b = 0.1 m; v_m = 0.13 m/s; ω = 16 rad/s (Figure 6).

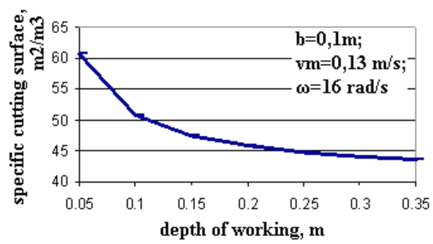

Fig. 6. *Influence of working depth on the variation of specific cutting surface of soil work with the digging machine*

Cutting surface area decreases with increasing work rate, which is observed from the diagram drawn for the concrete conditions of work: a = 0.3 m, b = 0.1 m, ω = 16 rad/s (Figure 7).

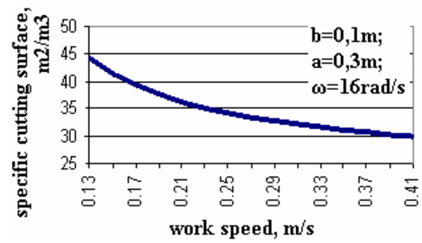

Fig. 7. *Influence of work speed on the variation of specific cutting surface of the work of the soil with digging machine*

Specific cutting surface is inversely proportional to the increase of the width of spades, which is observed from the diagram drawn for the concrete conditions of work, a = 0.3 m, v_m = 0.13 m/s, ω = 16 rad/s (Figure 8).

Specific mechanical work is the work needed for the deployment of the unit volume of soil, J/m^3. The specific mechanical work in working of the soil by the digging machine is calculated reporting the mechanical work done on a rotation of the crankshaft to the volume of soil displaced in a rotation, is:

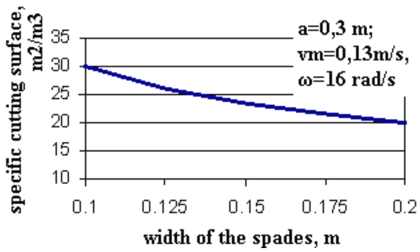

Fig. 8. *Influence of the width of the spades on the variation of the specific cutting surface in working the soil with the digging machine*

$$L_{sms} = \frac{L_{rot}}{V_{rot}} = \frac{P_{rot} \cdot \tau}{V_{rot}} \text{ [J]}, \quad (11)$$

where: L_{rot} is the mechanical work done by the digging machine at a rotation of the machine shaft in J; V_{rot} - volume of soil displaced in a rotation of the rotor shaft, in m^3; P_{rot} - crankshaft rotation required power in W; τ - time of a rotation, period of the crankshaft rotary motion, in s.

3. Results and Discussions

Movement during rotation is calculated as:

$$\tau = \frac{2\pi}{\omega} \text{ [rad/s]}. \quad (12)$$

Dislocated soil volume to a rotation of the crankshaft is calculated with:

$$V_{rot} = s \cdot a \cdot B \text{ [m}^3\text{]}, \quad (13)$$

where B is the width of the digging machine, in m.

Crankshaft rotation power required is calculated as:

$$P_{rot} = f \cdot G_{ms} \cdot v_m + \frac{\mu \cdot \rho \cdot g \cdot a^2 \cdot b \cdot v_m}{\sin\psi \cdot \cos\psi} \cdot z \cdot \frac{\omega \cdot t}{2\pi} + \frac{B \cdot a \cdot \rho \cdot v_m \cdot v_x^2}{2} + R \cdot \sin\psi \cdot v_m \text{ [W]}. \quad (14)$$

Making substitutions in equation (2) the formula of specific mechanical work changes in:

$$L_{sms} = \frac{f \cdot G_{ms}}{a \cdot B} + \frac{\mu \cdot \rho \cdot g \cdot a \cdot b \cdot z}{B \cdot \sin\psi \cdot \cos\psi} + \frac{\rho \cdot v_x^2}{2} + \frac{2\pi \cdot \rho \cdot g \cdot \text{tg}\,\psi \cdot v_m}{\varpi} \text{ [J/m}^3\text{]}. \quad (15)$$

In equation (15) notations correspond to those of equation (2).

Relationship (15) provides information on factors that influence specific mechanical work and also on the energy consumption of the digging work. Working depth, working speed, width of spades influences the specific mechanical work of the soil with digging machine with the soil.

To study the influence of each factor, in the theoretical part are considered the concrete conditions of theoretical study as: $f = 0.15$, $G_{ms} = 6100$ N, $\rho = 1500$ kg/m^3, $\mu = 0.36$ between soil and steel; tg $\psi_{med} = 0.62$; $\omega = 17$ rad/s; $B = 1.4$ m; $v_{xmed} = 4.37$ m/s; $b = 0.1$ m; $z = 6$; $a = 0.3$ m; $v_m = 0.4$ m/s.

From the graph shown in Figure 9 it results that the depth variation is inversely proportional to the variation of mechanical work specifically.

With increasing depth, occurs the decrease of the mechanical work needed in the processing of the unit volume of soil by digging.

From the graphics shown in Figures 10, 11 results that by increasing the working speed and width of the spades results an increase in the necessary mechanical work needed for processing the unit volume of the soil by digging.

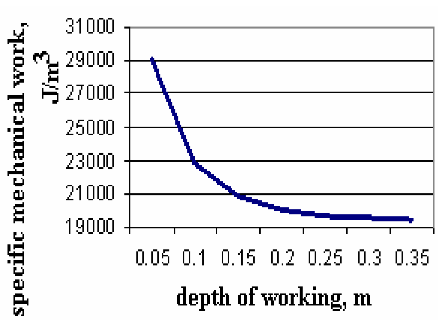

Fig. 9. *Influence of the depth of working on specific mechanical work of digging machine with the soil*

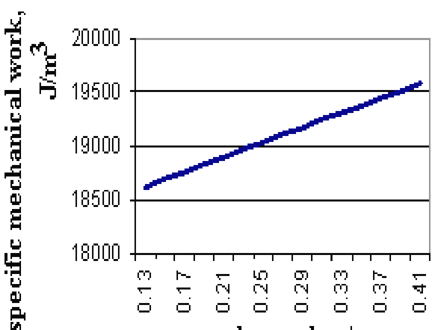

Fig. 10. *Influence of work speed on specific mechanical work of digging machine with the soil*

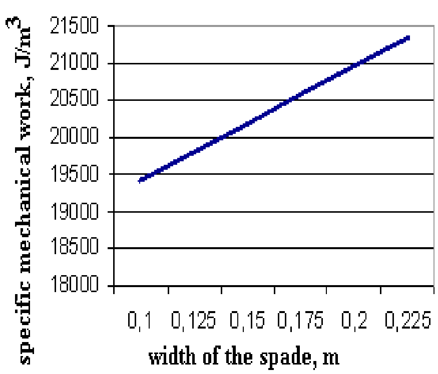

Fig. 11. *Influence of the width of the spades on the specific mechanical work of the soil with the digging machine*

The energetic optimization possibility application on the soil digging work based on the mathematical modeling made in this paper presuppose the collaboration between designers and manufactures for soil digging technical equipments, but also a superior training of the agriculture operators. These must assure optimal adjustment for technical system movement speed concordant to physical-chemical soil characteristics, to existent grass quantity etc. Through applying the research results obtained by the mathematical modeling proposed in this paper a contribution can be brought to the achievement of some agricultural works of superior quality in optimal economical conditions.

4. Conclusions

- Using the soil digging machine in preparing the germination bed in greenhouses is justified in working the soil at greater depths but with lower work speed.
- The digging machine which has wide spades requires a larger amount of mechanical work for the unit volume of the soil processed. Conclusion that refers to the width of the spades is benefic when.
- Designing the machine or when purchasing it, it can serve as basis for decision.
- The reduced dimensions of the deployed slices of the soil lead to higher specific surfaces, at the same time high energy consumption in working of the soil by digging machine.
- Higher working speeds result in high advances at moving forward, so big slices are deployed, reducing the energy required for processing by digging of the soil.
- Using the soil digging machine for preparation of the germination bed in greenhouses is justified through the working of the soil at greater depths.

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