STUDY OF FLAT MOVEMENT OF FLATTENING ROLLERS ALONG HEMP STEMS

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Abstract. The object of the study is technological processes, hemp stems, flattening of stems, flattening working organs. An analytical study of the interaction of working bodies of flattening rollers with hemp stems, the influence of the technological process on their parameters and modes of operation is the subject of the research. The main scientific results include the obtained mathematical model of interaction of smooth flattening rolls with a cone-shaped stem. Analytical dependencies, which determine the conditions of the beginning and the end of the interaction of the rollers with the stem depending on its parameters (the inner radius of the bottom part of the stem, the length of the stem, the angle of taper, the radius of flattening of the stem) and the radius of the rollers, have been established. Analytical dependencies of determining the maximum value of the generalizing reaction, the normal component of the reaction and the friction force under the conditions of interaction of the cone-shaped stem with smooth rollers depending on the intensity of the load, the radius of the rollers and the angle characterizing the maximum arc of contact of the stem with the roller are determined. The analytical dependence of the speed of movement of the rollers depending on the length of the stem, the weight of the rollers, the normal component of the reaction, the unit torque, the coefficient of rolling friction, the radius of the rollers is established. The results of the research are aimed at developing the theoretical foundations of technological operations of flattening hemp stems.

Keywords: stems of technical hemp, flattening of stems, flat movement of flattening rollers, generalizing reaction, friction forces.

Introduction

The processes of stem flattening are considered important factors that intensify the biological processes of preparing hemp trusts. Due attention is focused on the theoretical evaluation of the features of the interaction of stems with rollers along with experimental studies. The conducted analysis of the research results convincingly demonstrated the significant prospects for the application of the stalk flattening operation and their significant contribution to reducing costs and improving the quality of raw materials and products [1].

The degree of controllability (control) of the technological process, the uniformity of the process of destruction of the outer shell of the stems is increased due to the smooth change of the gap between the rollers that carry out the flattening of the stems [2].

The authors [3] noted the conditions for pulling the stems into the gap between the rollers. The specified movement of the stem into the gap between the rollers occurs under conditions where the horizontal component of the friction force exceeds the values of the horizontal component of the pressure of the rollers on the stem. Stems will be pushed out under opposite conditions.

The effectiveness of the flattening process, according to the conclusions [4, 5], is determined by a number of factors, the key among which are the diameter of the flattened rollers, the pressure and layer of stems, the thickness of the layer of the processed stems, their physical properties.

Theoretical analysis of the flattening process conducted by a number of authors investigated the forces that create the conditions for the separation of bast from the wood of the stem [6]. However, these studies were based on assumptions about constant parameters of the stems (diameter), as well as the constant value of the force.

Authors [6] set the working power of a pair of rollers and peripheral speed of rollers [6]. It is noted in the work that the thickness and degree of compression of the stems under the conditions of passage between two rollers depends on the diameters of the rollers and the coefficient of friction of the plant on the surface of the rollers. Thus, increasing the diameter and coefficient of friction provides compression of the stems of a larger diameter, which improves the conditions for the movement of the stems and increases the productivity of the compression process and the degree of grinding of the woody part of the stems [6].

Researchers have presented various models to model the energy costs of stem processing. The most famous and generally accepted among these theories are the laws of Kik, Rittinger and Bond in relation to size reduction. Their theories are presented in [7, 8]. However, in these studies, the stems are presented in the form of a cylinder. It is worth noting that the theoretical studies of the interaction models of stems with rollers considered above contained a simplified representation of the stem parameters. These mathematical models did not take into account the taper of hemp stems, which reduced the accuracy of describing contact conditions, determining reaction forces, and kinematic parameters of roller motion.

Materials and methods

The purpose of the work is to increase the efficiency of hemp production due to establishment of dependences, which describe flat motion of flattening rollers along the stem under conditions of resistance reaction according to linear law. This will make it possible to substantiate the parameters and operating modes of the rollers, which will create the prerequisites for increasing the efficiency of flattening processes. To achieve the goal, the following tasks were solved:

- to determine the conditions for the beginning and end of the interaction of the rollers with a conical stem depending on the stem parameters;
- to determine the analytical dependencies of the maximum values of the generalizing reaction, the normal component of the reaction and the friction force under the conditions of the interaction of a conical stem with smooth rollers;
- to determine the analytical dependency of the speed of movement of the rollers on the stem parameters, weight and force characteristics.

The following assumptions are accepted in the studies: the interaction of rollers with halves of hemp stems occurs at a constant interval between the rollers; the humidity and thickness of the walls of the stems are the same along the entire length; the thickness of the layer of hemp stems interacting with the rollers consists of one row; the stems are placed to the rollers with the upper (thin) part; the flattened stem does not contain a different kind of voids, if half of the flattening deformation is equal to the thickness of the stem wall; the pressure from the rollers on the stem changes according to the linear law with an increase in the diameter of the stem.

The object of the study is technological processes, hemp stems, flattening of stems, flattening working bodies. Analytical study of the interaction of the working elements of the compacting rollers with hemp stems, the influence of the technological process on their parameters and operating modes is included in the subject of the research.

The results of the theoretical research presented in the article are a continuation of previously conducted [9; 10].

Results and discussion

The resulting effect of the influence of several independent sources is equal to the sum of the effects caused by each influence separately, based on the principle of superposition. The interaction of halves of cone-shaped hemp stems with rolls was considered. The interaction of the rod with the rollers was considered under conditions of linear pressure change. Due to the torque proportional to the angle of rotation of the rollers φ_c (Fig. 1), torque $M_1 = C_1 \cdot \varphi_c$, where C_1 – constant, rolls without sliding move along the surface on which half of the elastic, cone-shaped stem is placed. Its axis is directed perpendicular to the axis of the rollers, and the stem relative to the rollers is directed by a thin (upper) part, the weight of the rollers P, radius R_1.

Let us assume that a generalized reaction acts on the roller from the side of the deformed stem R'_1, which forms a normal reaction N_1 and a friction force F_f. The generalized response of the stem varies linearly according to $R'_1 = q_1 \cdot dS$, where dS – increment of the area of action of the load intensity; q_1 – load intensity (N·m^{-2}).

In the general case, the reaction force of the stem is applied at the center of gravity A_1b_1M (Fig. 1). The triangle reflects the law of force change. The center of gravity of the triangle lies at one third of its height. The point of application of the reaction force of the stem is transferred as a result of the perpendicular to the horizontal line from the point of weight of the triangle. The horizontal line lies higher in the horizontal plane along which the rollers move. The frictional force of rolls performing flat motion without sliding is always applied in the instantaneous center of rotation of the rolls [11; 12]. The instantaneous center of rotation of the rollers is the point (Fig. 1).

Let us direct the axis x_1 through the center of inertia of the rollers O_1 parallel to the horizontal plane along which the rollers move. In accordance with the positive direction of the axis x_1, the angle of rotation of the rollers ξ_1 has a positive counterclockwise reference direction.

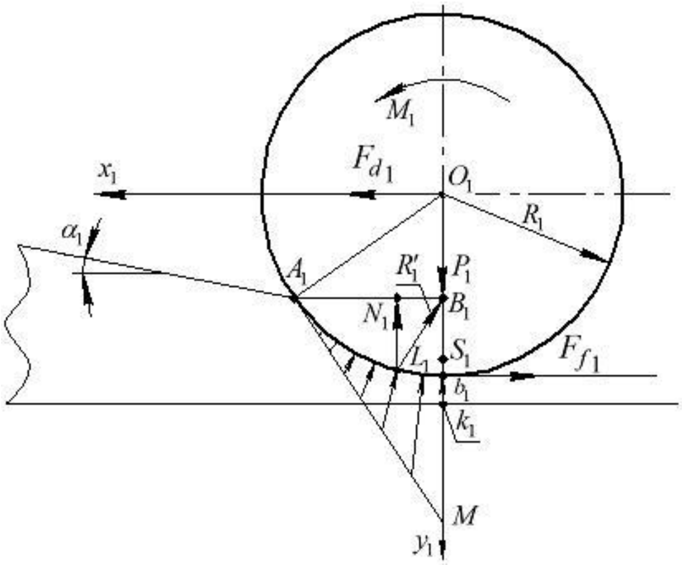

Fig. 1. **Diagram of planar movement of rollers along the elastic cone-shaped half of the hemp stem**

Let us use the theorem of change of kinetic energy of an invariable system of material points (rollers) [1; 5]

$$T_2 - T_1 = \sum_{k=1}^{n} A(F_k^e), \tag{1}$$

where T_1, T_2 – kinematic energy in the initial and final positions of the system of material points; $\sum_{k-1}^{n} A(F_k^e)$ – sum of the work of all internal and external forces of the system on the considered displacement.

Fig. 1 shows the external forces of the system: P_1 – weight of the rollers, the torque applied to the rollers M_1, the normal reaction N_1 is shifted in the direction of movement relative to the center of inertia of the rollers by a distance equal to the rolling coefficient f_{k1}, the friction force of the rollers F_f, α_1 – taper angle of the rod, F_{d1} – driving force.

We give an elementary displacement dx of the center of inertia O_1 of the rollers parallel to the horizontal plane. Note that

$$dx = R_1 \cdot d\xi_1, \tag{2}$$

where $d\xi_1$ – elementary angular displacements of the rollers.

The work of all external forces of the system is calculated

$$\delta A = \delta A(F_{d_1}) + \delta A_{m.K_1O_1} + \delta A(R_1) + \delta A(m) + \delta A(F_f). \tag{3}$$

Then

$$\delta A(F_{d_1}) = F_{d_1} \cdot dx, \delta A_{m.K_1O_1} = M_1 \cdot d\xi_1. \tag{4}$$

Note that $M_1 = N_1 \cdot f_{k1}$

$$\delta A_{m.K_1O_1} = N_1 \cdot f_{k_1} \cdot \frac{dx}{R_1}. \tag{5}$$

Let us define $\delta A(M_1) = M_1 \cdot d\xi$, then

$$\delta A(M_1) = \eta \cdot \xi \cdot \frac{dx}{R_1}, \tag{6}$$

where η – is a constant.

The interaction between the rollers and the stem begins when the stem with an outer radius r_{12} touches the side surface of the rollers. The deformation of the stem (according to the assumption) is $(r_{12} - r_n)$. Then

$$\xi_1 = \arcsin\left(\sqrt{(r_{12} - r_n) \cdot (2 \cdot R_1 - (r_{12} - r_n))} \big/ R_1\right). \tag{7}$$

Dependence (7) determines the conditions (angle values ξ_1) under which the outer radius R_1 rollers interact with the stem, the smallest value of the upper part radius being r_{12}, and the flattening radius r_n. The moment when the rollers stop interacting with the stalk is characterized by the condition when the base of the stalk has an outer radius r_{22} equal to

$$r_{22} = r_{12} + l_{cm} \cdot tg\alpha_1. \tag{8}$$

As a result of simple transformations, we obtained an expression for determining the angle ξ_2, which characterizes the completion of the interaction of the rollers with the stem

$$\xi_2 = \arcsin\left(\sqrt{\left((r_{12} - r_n) - l_{st} \cdot tg\alpha_1\right) \cdot \left(2 \cdot R_1 - (r_{12} - r_n) + l_{st} \cdot tg\alpha_1\right)} \big/ R_1\right). \tag{9}$$

That is $0 \le x \le l_{st}$, and the angle ξ

$$\xi_1 \le \xi \le \xi_2, \tag{10}$$

where ξ_1 – determined by dependence (7), and ξ_2 – (9).

The conditions of the beginning (angle ξ_1) and end (angle ξ_2) of the interaction of the rollers with the conical stem are established depending on the stem parameters r_{12} – inner radius of the stem butt, l_{st} – stem length, α_1 – taper angle, r_n – stem flattening radius) and the roller radius R_1).

Changing the position of the rollers (moving to the left by dx) leads to a change (increase) in the resulting resistance reaction. Accordingly, this leads to a change in the normal component of the reaction N_1 and the friction force. Under such conditions, the maximum values of the generalized reaction, the normal component of the reaction, and the friction force will be $x = l_{st}$, $\xi = \xi_2$ [1, 4]

$$R'_{1_{\max}} = q_1 \cdot \frac{1}{2} \cdot R_1^2 \cdot \sin\xi_2 \cdot (\sin\xi_2 \cdot tg\xi_2 + \cos\xi_2) - \frac{2 \cdot \pi \cdot R_1}{360} \cdot \xi_2. \tag{11}$$

$$N_{1_{\max}} = \frac{1}{2} \cdot R_1^2 \cdot \sin\xi_2 \cdot \cos\frac{\xi_2}{3} \cdot (\sin\xi_2 \cdot tg\xi_2 + \cos\xi_2) - \frac{2 \cdot \pi \cdot R_1}{360} \cdot \xi_2, \tag{12}$$

$$F_{f_{\max}} = \frac{1}{2} \cdot R_1^2 \cdot \sin\xi_2 \cdot \sin\frac{\xi_2}{3} \cdot (\sin\xi_2 \cdot tg\xi_2 + \cos\xi_2) - \frac{2 \cdot \pi \cdot R_1}{360} \cdot \xi_2. \tag{13}$$

Analytical dependencies (11-13) determine the maximum value of the generalized reaction, the normal component of the reaction, and the friction force under the conditions of interaction of a conical stem with smooth rollers, depending on the load intensity q_1, the radius of the rollers R_1, and the angle ξ_2.

$$\delta A = F_{d_1} \cdot dx - N_1 \cdot f_{k_1} \cdot \frac{dx}{R_1} + \eta \cdot \xi \cdot \frac{dx}{R_1}. \tag{14}$$

To determine the sum of the work of external forces on the final displacement x, we took a definite integral in the 0 range from to l_{st}. After integrating, we obtained

$$A = l_{st}\left(F_{d_1} - N_1 \cdot f_k \cdot \frac{1}{R_1} + \eta \cdot \xi \cdot \frac{1}{R_1}\right). \tag{15}$$

We calculated the kinetic energy of the system consisting only of rollers. At the initial moment the system is at rest $T_1 = 0$. Kinematic energy in the final position $T_1 = T_{2_{O1}}$. We marked V_{O1} the desired speed of the point O_1 of the rollers. Then $V_{O1} = \omega \cdot R_1$, where ω – is the angular velocity of rotation of the rollers. The kinetic energy of rollers performing a planar motion was calculated according to the dependence

$$T_{2_{O_1}} = \frac{3 \cdot P_1 \cdot V_{O_1}^2}{4 \cdot g}. \quad (16)$$

Substituting the obtained values into dependence (1), we obtain

$$\frac{3}{4 \cdot g} \cdot P_1 \cdot V_{O_1}^2 = l_{st} \left(F_{d_1} - N_1 \cdot f_k \cdot \frac{1}{R_1} + \eta \cdot \xi \cdot \frac{1}{R_1} \right). \quad (17)$$

Where

$$V_{O_1} = \sqrt{\frac{4 \cdot l_{st} \cdot g}{3 \cdot P_1} \cdot \left(F_{d_1} - N_1 \cdot f_k \cdot \frac{1}{R_1} + \eta \cdot \xi \cdot \frac{1}{R_1} \right)}. \quad (18)$$

Fig. 2 shows the dependence of the speed of movement of the rollers on the length of the stem and the radius of the rollers.

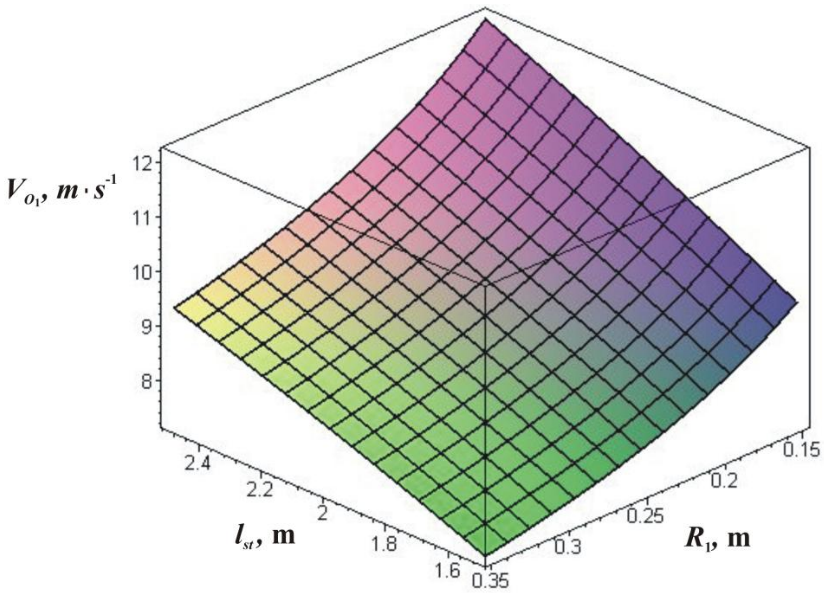

Fig. 2. **Dependence of the speed of movement of the rollers on the length of the stem and the radius of the rollers**

Equation (18) determines the speed of movement of the rollers from the length of the stem, the weight of the rollers, the normal component of the reaction, the unit torque, the coefficient of rolling friction, and the radius of the rollers.

Conclusions

1. The conditions of the beginning (angle ξ_1) and the end (angle ξ_2) of the interaction of the rollers with the conical stem are established depending on the parameters of the stem (r_{12} – inner radius of the stem butt, l_{st} – stem length, α_1 – taper angle, r_n – flattening radius of the stem) and the radius of the rollers R_1.
2. Analytical dependencies determine the maximum value of the generalizing reaction, the normal component of the reaction and the friction force under the conditions of the interaction of the conical stem with smooth rollers depending on the load intensity q_1, the radius of the rollers R_1 and the angle ξ_2, which characterizes the maximum arc of contact of the stem with the roller.

3. Dependence determines the speed of movement of the rollers depending on the length of the stem, the weight of the rollers, the normal component of the reaction, the unit torque, the coefficients of rolling friction, the radius of the rollers.

Author contributions

Conceptualization, V.S. and Y.S.; methodology, V.S. and Y.S.; software, V.S., I.D., Y.S., M.T. and Vit.S; validation, V.S., I.D., Y.S., M.T. and Vit.S.; formal analysis, V.S., I.D. and Y.S.; investigation, V.S. and Y.S.; data curation, V.S., I.D., Y.S. and M.T.; writing – original draft preparation, V.S. and Y.S.; writing – review and editing, V.S., I.D., Y.S., M.T., Vit.S. and L.P.; visualization, V.S., Y.S. and L.P.; project administration, V.S., Y.S. and M.T.; funding acquisition, M.T., Vit.S., L.P. All authors have read and agreed to the published version of the manuscript.

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