

Vitamin-grass flour is the main component of mixed fodders intended for all types of live-stock and poultry. Earlier and currently, the vitamin-grass flour has been prepared from legumes by a high-temperature drying technique. However, existing techniques have high operating costs and require very expensive technical tools.

To reduce the specific operating costs and the price of equipment in the production of VGF, a technique has been proposed that involves the main drying of grass to a moisture content of 30–35 % on a swath while the post-drying of grass is performed in a small-sized channel under the haystack without air heating. Next, the dried mass is pre-crushed. At the same time, the delicate leaf part of the hay, while falling between the side walls of hammers and counter-hammers, is ground and finely crushed, and the stems are processed into large fractions. From pre-crushed hay, the leaf part is separated and fed into the crusher to produce flour.

In this case, the main machine that determines the performance of the line is the separator of the leaf part of the grass.

The results of the theoretical research have established the speed and acceleration of hay movement on the surface of the sieve. These values determine the productivity of separation of the leaf part from pre-crushed hay and the reliability of the selected structural and technological scheme of the separator. The production tests have confirmed the reliability and economic efficiency of the proposed technique. Comparing the proposed technique for obtaining vitamin-grass flour by existing high-temperature methods has shown that the carotene content in flour was 1.6 times higher while the specific operating costs and equipment price were 6–7 times lower

Keywords: vitamin-grass flour, high-temperature drying of grass, separator of hay leaves, sieve speed, sieve acceleration

DETERMINING THE SPEED AND ACCELERATION OF THE SEPARATOR FOR GRASS LEAF PART IN HORIZONTAL AND VERTICAL DIRECTIONS

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Received date 12.03.2021

Accepted date 28.09.2021

Published date 29.10.2021

How to Cite: Abilzhanuly, T., Keshuov, S., Rzaliyev, A., Zhortuylov, O., Zhumatay, G., Abilzhanov, D., Karmanov, D., Boranbayev, B. (2021). Determining the speed and acceleration of the separator for grass leaf part in horizontal and vertical directions. *Eastern-European Journal of Enterprise Technologies*, 5 (1 (113)), 41–50. doi: <https://doi.org/10.15587/1729-4061.2021.242957>

1. Introduction

Vitamin-grass flour (VGF) is the main component of mixed fodders intended for all types of livestock and poultry; its composition includes the highest content of carotene and minerals [1]. VGF is prepared from legume herbs by a high-temperature drying technique. However, when preparing 1 ton of VGF, existing plants consume 200–250 liters of diesel fuel and 73–101.5 kW of electricity [2]. Therefore, due to the high unit operating costs, many farms are currently not engaged in the preparation of VGF.

Devising a new VGF preparation technique, which could reduce specific operating costs, as well as designing machines for its implementation, would resolve a relevant issue in the agricultural industry.

2. Literature review and problem statement

It is known that the use of grass vitamin flour in livestock diets can increase the average daily milk yield by 12 %, cattle weight gain – by 8–15 %, fattening pigs – by 10–18 %. At the same time, feed costs per unit of livestock products are reduced by 10–20 % [3].

Previously, VGF was prepared on assemblies of the AVM-0.4A type. Diesel fuel consumption by these units reached up to 120 kg/h. The weight of the assembly is 9,900 kg [4]. Various modifications of the AVM-type units were also used to dry the grass.

Work [5] investigated the thermal balance of drying units of the AVM type. The use of such assemblies is limited due to the fact that the application of high-temperature drying

technology requires large specific operating costs and capital investments.

In addition, vitamin-grass flour was produced at the drying and grinding line Yavajra (OOO «Agro Profile Plus», Russia) [6]. In that unit, drying is carried out by a short-wave drying plant to a temperature of 90 °C, under a certain exposure. The price of this plant is 15 million rubles. The line's characteristics indicate that a high-temperature drying technique is used for drying grass while the plant's price is very high. Therefore, the use of that installation at peasant farms does not make much sense economically.

Work [7] describes a technique for the infrared drying of plant raw materials. The authors give results from preliminary exploratory studies into the substantiation of parameters and modes of the technological process of drying plant materials and note the expediency of designing a multipurpose drying installation.

Paper [8] reports the results from an experimental study involving an experimental sample of the drum dryer with an infrared heat source. The authors derived dependences of changes in the temperature of the drying agent and the moisture content of the crushed plant mass on the drying time.

The influence exerted on the milk productivity of cows by feeding them with vitamin-grass flour from *Leuzea safflower* was investigated in [9]. When feeding cows with a 10 % content of vitamin-grass flour from *Leuzea safflower* as part of the concentrate diet, the most effective use of protein and energy from the nutrients of the used diet in dairy products was observed.

When addressing the task of increasing the efficiency of livestock production, there is an issue related to relaunching the production of grass flour [10].

Paper [11] considers the relevance and effectiveness of the organization of production of granules from vitamin-grass flour in the Krasnoyarsk Territory of the Russian Federation.

Study [12] proposed the production of vitamin-grass flour as an alternative to imported synthetic vitamins.

The above review reveals that currently used drying and grinding lines and installations operate based on high-temperature drying. However, they are very expensive, so their use under economic conditions is limited.

At present, many authors also note the relaunching of vitamin-grass flour production and the development of technical means that ensure VGF preparation at reduced operating costs.

Based on this, a new VGF production technique from the leaf part of grasses [13] is proposed.

Designing a line to prepare VGF from the leaf part of grasses started in 2012. Theoretical and experimental studies were carried out to substantiate the parameters of the machines for a line to produce VGF from the leaf part of grasses.

The results of the theoretical research substantiated the kinematic parameters for a separator of the leaf part of grasses [14]. Experimental studies and production tests were carried out to justify the technological parameters for a VGF line [15]. The results of the experimental studies helped establish the optimal values for the rotational speed of the sieve, the radius of the crank, and the angle of inclination of the separator sieve [16]. To increase the productivity of the process of separation of the leaf part of the grass, the separator is equipped with a special drum that provides tossing and loosening of the thick layer moved over the surface of the sieve [17]. To facilitate the operator's work, a small-sized feeder-dispenser was designed; the theoretical

and experimental studies were conducted to substantiate its parameters [18].

However, the velocities and accelerations of the separator sieve in the horizontal and vertical directions and the speed of hay movement over the surface of the sieve were not determined.

The importance of these technological parameters of the separator is due to the fact that they determine the performance and correctness of the choice of the structural and technological scheme of the separator.

3. The aim and objectives of the study

The purpose of this study is to substantiate the parameters for a separator of the leaf part of grass from pre-crushed hay, which ensures the preparation of high-class VGF.

To accomplish the aim, the following tasks have been set:

- to theoretically determine the speed and acceleration of the sieve separator of the leaf part of grass in the vertical and horizontal directions;
- to determine the condition for the movement of the stems over the surface of the sieve depending on the rotation of the crank;
- to determine the speed of hay movement over the surface of the sieve;
- to conduct production tests of a VGF preparation line.

4. The study materials and methods

When determining the speed and acceleration of the sieve separator of the leaf part of grass, we applied a method of transforming the simplest movements from the theoretical mechanics and the theory of mechanisms and machines.

The actual values of the speed of movement of pre-crushed hay over the surface of the sieve were obtained as a result of one-factor experimental studies.

To obtain the results from production tests of a VGF preparation line, we applied test methods of agricultural machinery. To determine the content of carotene in the resulting flour, the method of chemical analysis of feed was used.

5. Results of the study into the substantiation of technological parameters for a separator of leaf part of grass

5.1. Results of the theoretical study to determine the speed and acceleration of the separator sieve

To solve the set task, a new technique to prepare VGF from the leaf part of grass and a hypothesis have been proposed. To significantly reduce the specific operating costs, it is necessary to perform the main operation – drying the grass on a swath to a moisture content of 30–35 %. At the same time, the main moisture from the plant is removed on the swath while some losses of carotene and vitamins are compensated for by preparing VGF from the leaf part of grass [13]. This is due to the fact that the content of carotene and vitamins in the leaf part of grass is 10–12 times greater than that in the stem part of the plant [1].

According to the proposed technique, the dried grass is picked from the swath by a special pick-up shredder. In this case, all rows of counter-hammers are removed from

the grinding chamber of the pick-up shredder, that is, it is used to pick the grass from the swath and load it into the body of a vehicle. In this case, the pick-up shredder executes another important operation – the destruction of the stem structure, ensuring the rapid drying of the grass to the required moisture content.

Next, the gathered mass is transported under the canopy where the designed line for VGF preparation from the leaf part of grass is installed (Fig. 1) [14–18].

First, the dried grass is loaded onto channel 1 under the haystack for final drying. In the channel under the haystack, the grass is dried to a moisture content of 14...16%. Next, the dried mass, through feeder-dispenser 3, is fed into a sieve-less grinder of coarse forage. In the grinding chamber, another important process is performed: the delicate leaf part of the hay, when it gets between the side walls of hammers and counter-hammers, is ground and crushed into small fractions up to 10–15 mm long. And the stem part is crushed into large fractions with a particle length of more than 20 mm. This difference in the length of grinding of the leaf and stem parts of the pre-crushed hay ensures the separation of the leaf part of grass.

Next, the separated leaf part of the hay is fed into the crusher to produce flour. To isolate the leaf part of grass from the pre-crushed hay, a special separator was designed; it was granted a patent by the Republic of Kazakhstan [17].

The designed line has a mass of 2,000 kg and the power of the installed electric motors of 41.75 kW; therefore, the line has 5–7 times less weight and cost compared to existing machines. At the same time, the productivity of the entire line depends on the performance of the separator of the leaf part of grass (Fig. 2).

The theoretical and experimental studies were carried out to substantiate the separator parameters [14–18]. However, the instantaneous velocities and accelerations of the sieve in the horizontal and vertical directions have not been determined, depending on the angle of rotation along the circumference of the crank rotation.

According to the kinematic scheme, the beginning of the separator sieve would be set into a rotational movement with a certain radius, and its end would be set into an oscillating movement relative to the freely installed lever (Fig. 3). Analysis of the kinematic scheme (Fig. 3) of the separator shows that the speed and acceleration of the sieve in the horizontal and vertical directions exert an important influence on the performance of the line.

There are results of research on determining the speed and acceleration of the crank-connecting rod mechanism and the mechanism of a drive of mowing

units in the horizontal direction [19, 20]. However, it is practically important to determine the actual values of the speed and acceleration of the sieve in the horizontal and vertical directions.

In earlier studies, the optimal parameters for a separator of the leaf part of grass were determined [14–16]: the angle of inclination of the sieve is $\alpha=15^\circ$; crank radius – $R=0.015$ m; crank rotation speed – $n=305$ min⁻¹; sieve length – $L=1.0$ m; sieve width – $B=0.6$ m.

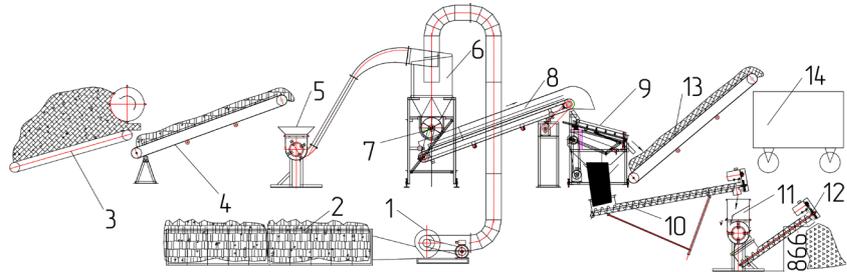


Fig. 1. Structural and technological scheme of the LVM-0,4 line to prepare vitamin-grass flour: 1 – fan; 2 – channel under the haystack; 3 – feeder-dispenser; 4 – transverse conveyor; 5 – sieve-less shredder; 6 – cyclone; 7 – sluice gate; 8 – conveyor; 9 – sieve separator; 10 – auger; 11 – sieve crusher; 12 – auger; 13 – conveyor; 14 – feed dispenser

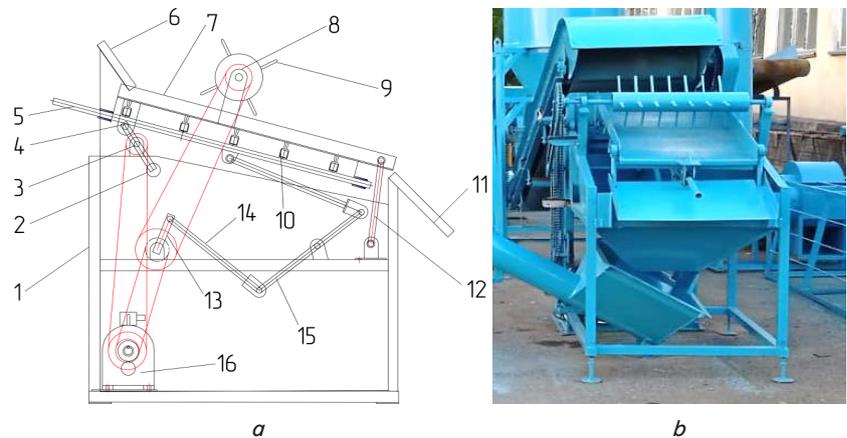


Fig. 2. Separator of the leaf part of grass: *a* – structural and technological scheme of the separator: 1 – frame; 2 – sinker; 3 – crank drive shaft; 4 – axis of rotation of the beginning of the sieve; 5 – slider for brush drive; 6, 11 – trays; 7 – sieve; 8 – leveling drum; 9 – finger; 10 – brush; 12 – lever; 13 – crank; 14 – connecting rod; 15 – lever; 16 – gear motor; *b* – general view of the separator

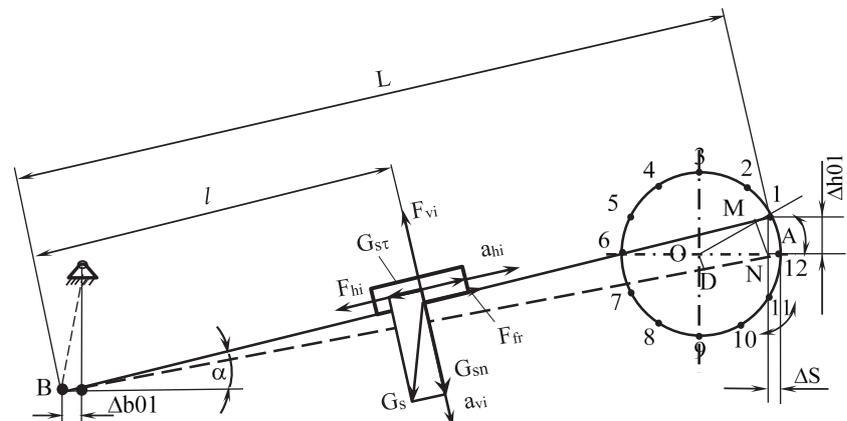


Fig. 3. Kinematic scheme of the separator sieve drive

Hence it is known that the radius of the crank $R=15$ mm. In this case, when the beginning of the sieve is located at point A , the angle of its inclination $\alpha=15^\circ$. In a given case when the beginning of the sieve would be at point 3 , the change in the angle of inclination of the sieve is only $24'$, so these changes can be neglected.

To determine the speed and acceleration of the sieve in the horizontal direction, consider the OAD triangle. One can see that when the crank is rotated along the first quarter, the complete movement of the sieve DS_p is equal to the length AD . In this case, depending on the value of the rotation of the crank, the movement of the sieve in the horizontal direction is determined as follows:

$$\begin{aligned} \Delta S_p &= \Delta S \cdot \cos \alpha = \\ &= R \cos \alpha (1 - \cos \varphi), \end{aligned} \quad (1)$$

where ΔS is the diametrical displacement of the beginning of the sieve, m; φ is the angle of rotation of the crank.

To determine the value for the vertical movement of the sieve, consider the $MN1$ triangle; it follows that the value of the vertical movement MN or Δh_p is determined as follows:

$$\Delta h_p = \Delta h \cdot \cos \alpha = R \cos \alpha \cdot \sin \varphi. \quad (2)$$

In this case, the movement of the sieve in the vertical direction depends on the location of the point on the sieve.

For example, a value of the vertical movement of the sieve at point C is determined as follows:

$$\Delta h_{pc} = \frac{l}{L} \Delta h_p = \frac{l}{L} R \cos \alpha \sin \varphi, \quad (3)$$

where l is the distance from the end of the sieve to point C , m; L is the length of the sieve, m.

To determine the rate of the beginning of the sieve in the horizontal direction, it is necessary to calculate the derivative from (1) by time:

$$\begin{aligned} v_h &= \frac{dS_p}{dt} = R \cos \alpha (1 - \cos \omega t)' = \\ &= -R \cos \alpha (\cos \omega t)' (\omega t)' = \\ &= -R \cos \alpha (-\sin \omega t) \cdot \omega = R \omega \cos \alpha \sin \omega t. \end{aligned} \quad (4)$$

To determine the acceleration of the sieve, we shall take the derivative from (4) by time:

$$a_h = \frac{dv_h}{dt} = (R \omega \cos \alpha \cdot \sin \omega t)' = R \omega^2 \cos \alpha \cdot \cos \omega t. \quad (5)$$

The vertical speed of the sieve, depending on the angle of rotation of the radius, is determined from the following formula:

$$v_v = \frac{dh_p}{dt} = (R \cos \alpha \cdot \sin \omega t)' = R \omega \cos \alpha \cdot \cos \omega t. \quad (6)$$

To determine the acceleration of the sieve, we also take the derivative from formula (6) by time:

$$a_v = \frac{dv_v}{dt} = (R \omega \cos \alpha \cdot \cos \omega t)' = -R \omega^2 \cos \alpha \cdot \sin \omega t. \quad (7)$$

Thus, we have derived analytical expressions to determine the speed and acceleration of the beginning of the sieve separator of the leaf part of grass from pre-crushed hay.

Using these analytical expressions, the velocities and accelerations of the sieve in the horizontal and vertical directions have been determined (Fig. 4–7).

The calculation results showed that the maximum value of the sieve velocity in the horizontal direction is 0.4624 m/s.

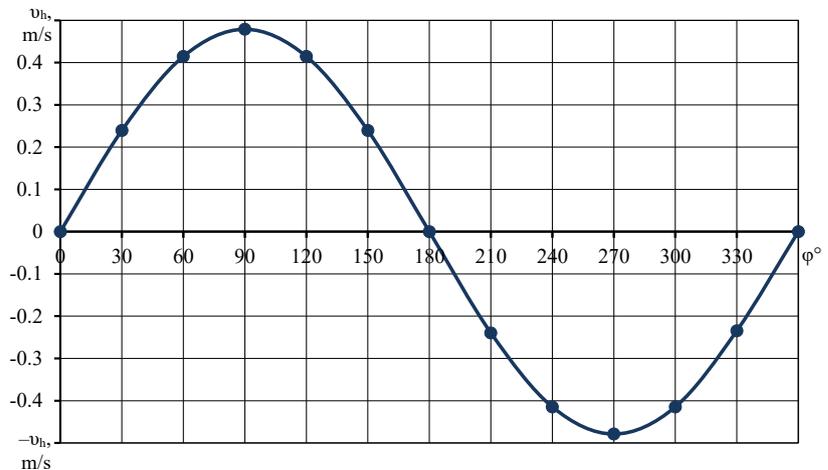


Fig. 4. The horizontal speed value of the separator sieve depending on the angle of crank rotation

When considering the kinematic scheme of the sieve, the direction of rotation is also important.

5. 2. Determining the condition of stem movement over the surface of the sieve depending on the crank rotation

If the crank rotates in the specified direction, then when turning along the first and second quarters of the circumference of its rotation, the sieve moves to the left. Analysis of the horizontal acceleration plot shows that when rotating in the first quarter, the value of horizontal acceleration decreases (Fig. 5).

In this case, the intensity of the decrease at the end of the quarter is maximum, that is, the sieve moves with braking, and the horizontal force of inertia is directed downward in the direction of movement of the sieve.

Analysis of the vertical acceleration also shows that at the end of the quarter the change in the vertical acceleration decreases, that is, the vertical displacement is also accompanied by braking, and the force of inertia is directed upwards (Fig. 3).

In this case, a value for the equivalent force is determined as follows:

$$F_r = F_{hi} + G_s \sin \alpha - F_{fr}, \quad (8)$$

where F_{hi} is the force of inertia; G_s is the gravity of the stems, N; F_{fr} is the friction force of the stem, N.

Since the actual acceleration values acting on the stem in the horizontal and vertical directions are calculated, formula (8) can be rewritten as follows:

$$\begin{aligned} F_r &= m \cdot a_{hi} + mg \sin \alpha - m(g \cos \alpha - a_{vi}) f = \\ &= m(a_{hi} + g \sin \alpha) - m(g \cos \alpha - a_{vi}) f. \end{aligned} \quad (9)$$

When turning the crank along the front quarter of the circumference of its rotation, the condition for moving the stems along the surface of the sieve is expressed as follows:

$$a_{hi} + g \sin \alpha > (g \cos \alpha - a_{vi}) \cdot f. \quad (10)$$

Fig. 5, 7 demonstrate that the values of the horizontal and vertical acceleration of stems equally vary within 0...14.76 m/s². In this case, to solve (10), it is necessary to determine the average value of the acceleration of the stems.

The horizontal acceleration average value is determined from the following formula [21]:

$$\begin{aligned} a_{ha} &= \frac{\int_0^{\frac{\pi}{2}} R\omega^2 \cos \alpha \cdot \cos \varphi d\varphi}{\frac{\pi}{2}} = \\ &= \frac{2R\omega^2 \cos \alpha}{\pi} \int_0^{\frac{\pi}{2}} \cos \varphi d\varphi = \\ &= \frac{2R\omega^2 \cdot \cos \alpha}{\pi} (\sin \varphi) \Big|_0^{\frac{\pi}{2}} = \\ &= \frac{2R\omega^2 \cdot \cos \alpha}{\pi} \left(\sin \frac{\pi}{2} - \sin 0 \right) = \\ &= \frac{2R \pi^2 n^2 \cdot \cos \alpha}{900} = \frac{2R\pi n^2 \cdot \cos \alpha}{900} \\ &= 0.007Rn^2 \cdot \cos \alpha. \end{aligned} \quad (11)$$

It should be noted here that the average value of vertical acceleration is also determined from formula (11). Substituting the known values of the crank radius and the speed of crank rotation, the average values of the horizontal and vertical acceleration of the stems moving along the surface of the sieve have been determined:

$$a_{hm} = a_{vm} = 9.42 \text{ m/s}^2.$$

To determine the conditions of movement, we give the values of the parameters: $\alpha = 15^\circ$; $\sin 15^\circ = 0.2558$; $\cos 15^\circ = 0.9659$. A value for the coefficient of friction was determined by a special experiment. In this case, it became known that the beginning of the movement of the stems of pre-crushed alfalfa with a moisture content of 15.38 % was executed over an inclined steel surface at its angle of inclination equal to $24^\circ 34'$, that is, $\text{tg } 24^\circ 34' = 0.4571$, or $f = 0.457$.

$$9.42 + 9.81 \times 0.2558 > (9.81 \times 0.9659 - 9.42) \times 0.457.$$

$$11.93 > (9.47 - 9.42) \times 0.457.$$

$$11.93 > 0.023.$$

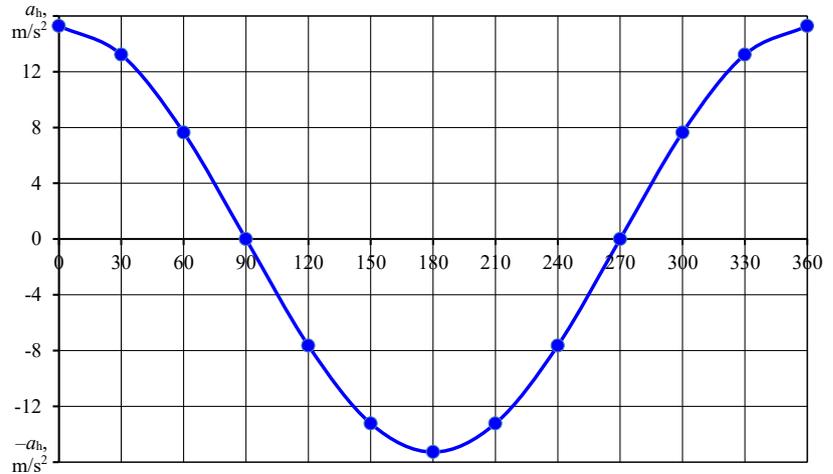


Fig. 5. Dependence plot of the horizontal acceleration of the separator sieve on the angle of crank rotation

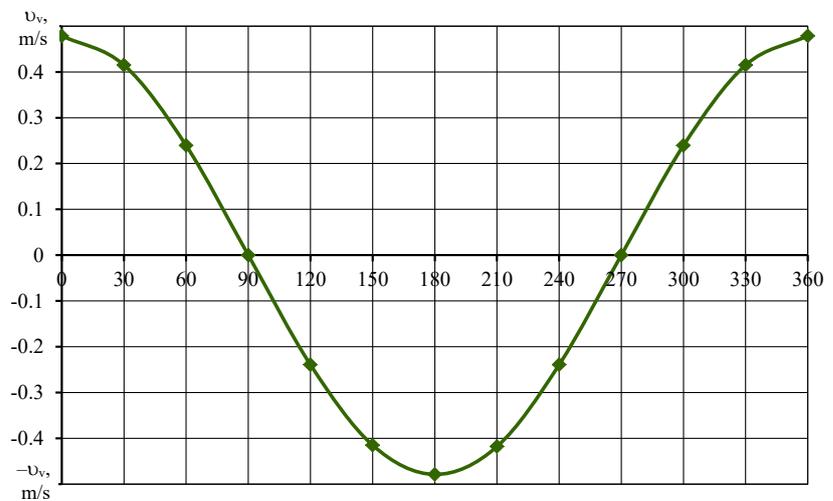


Fig. 6. The vertical speed value of the separator sieve depending on the angle of crank rotation

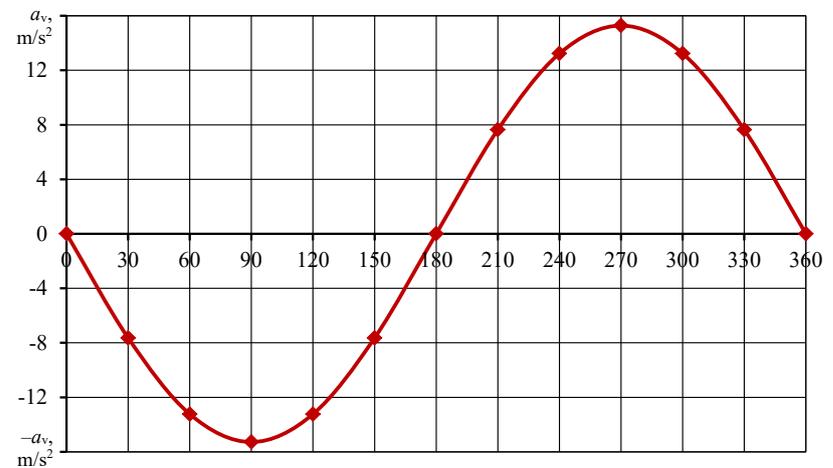


Fig. 7. Dependence plot of the vertical acceleration of the separator sieve on the angle of crank rotation

These calculations show that, in this case, there are only forces acting on the stem in the course of its movement, and there is almost no friction force.

The vertical force is slightly less than the normal component of the gravity of the stems. At the same time, it can

be argued that the crushed hay on the sieve is tossed, thereby entering the state of suspension, that is, it is in a state of «weightlessness». In addition, it should be noted that the correspondence of the average value of vertical acceleration to the value of g shows the optimality of the rotational speed of the beginning of the sieve.

Thus, when the crank is rotated along the first quarter of the circumference of its rotation, the hay follows a sufficient accelerated movement down the surface of the sieve.

When one rotates the crank in the second quarter, one can see that the value of the horizontal acceleration increases but the intensity of the change at the end of the quarter decreases. This indicates that the force of inertia is also directed downward in the direction of motion of the sieve. In this case, the vertical acceleration decreases, and the intensity of the acceleration change at the end of the quarter increases, that is the vertical force of inertia is also directed downwards (Fig. 8).

In this case, the equivalent force is determined as follows:

$$F_r = F_{hi} + G_s \sin \alpha - (F_{vi} + G_s \cos \alpha) f. \tag{12}$$

At the same time, the condition of moving the stems over the surface of the sieve is expressed in the following form:

$$a_{hi} + g \sin \alpha > (a_{vi} + g \cos \alpha) f. \tag{13}$$

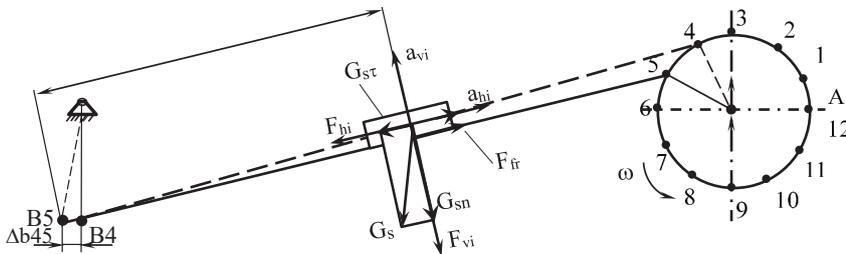


Fig. 8. Diagram of the forces acting on the stem when the crank rotates along the circumference in the second quarter

Solving (13) produces the following:

$$11.93 > (9.42 + 9.47) \times 0.457.$$

$$11.93 > 8.163.$$

These calculations also show that the value of the force acting on the stem in the course of its movement is greater than the force acting in the opposite direction, that is, the hay continues to move accelerated down the surface of the sieve.

When the crank is rotated along the third quarter, the direction of horizontal movement of the sieve changes. The horizontal acceleration value decreases. The intensity of the acceleration decrease increases, and, at the same time, the horizontal force of inertia is directed along the course of the sieve movement while the vertical force of inertia would be directed downwards, contributing to an increase in the friction force (Fig. 9).

In this case, the equivalent force is determined as follows:

$$F_r = G_s \sin \alpha + (G_s \cos \alpha + F_{vi}) f - F_{hi}. \tag{14}$$

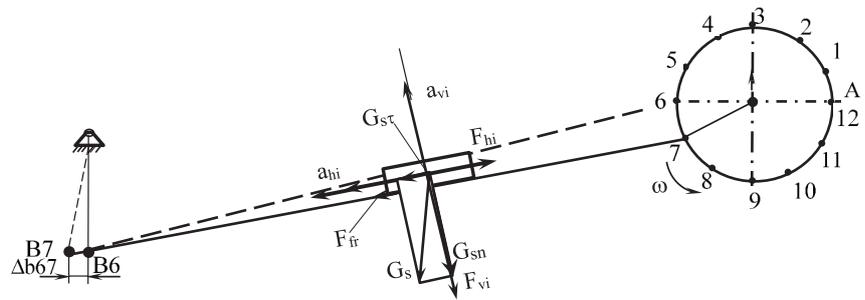


Fig. 9. Diagram of the forces acting on the stem when the crank rotates along the circle in the third quarter

The condition for moving the stems over the surface of the sieve takes the following form:

$$G_c \sin \alpha + (G_c \cos \alpha + a_{vi}) f > a_{hi}. \tag{15}$$

$$9.81 \times 0.2558 + (9.81 \times 0.9659 + 9.42) \times 0.457 > 9.42.$$

$$2.51 + (9.47 + 9.42) \times 0.457 > 9.42.$$

$$11.14 > 9.42.$$

In this case, the value of the force acting on the stem in the course of its movement was greater than the force of inertia, so the hay continues to move accelerated along the surface of the sieve.

In addition, in the third quarter, the movement of the sieve is directed towards the beginning of the sieve, that is against the movement of the mass over the surface of the sieve. All this also contributes to the movement of the stems down the surface of the sieve.

The horizontal movement of the sieve in the fourth quarter is directed towards the movement of hay over the surface of the sieve. At the same time, the horizontal acceleration increases while the intensity of its change at the end of the quarter decreases, that is, the sieve moves with braking and the horizontal force of inertia is directed against the movement of the mass.

In this case, the beginning of the sieve rises sharply upwards while the intensity of the decrease in the vertical acceleration increases. The vertical force of inertia would be directed upwards.

An equivalent force is defined as follows:

$$F_r = G_s \sin \alpha + (G_s \cos \alpha - F_{vi}) f - F_{hi}. \tag{16}$$

In this case, the friction force is zero and, in the course of the movement of the stems, only the tangential component of gravity is in action.

If we consider that in the remaining quarters of the circumference of the crank rotation, the hay receives intense movement over the surface of the sieve and, in the fourth quarter the movement of the sieve, is directed towards its beginning. Therefore, in the fourth quarter, the appearance of a horizontal force of inertia against the movement of mass does not have a significant effect on the movement of the stems over the surface of the sieve.

Thus, with the specified direction of crank rotation, the emergence of vertical acceleration also contributes to the intense movement of the stems down the surface of the sieve.

These results of theoretical studies show the correctness of the selected structural and technological scheme of the separator of the leaf part of grass from pre-crushed hay.

5.3. Determining the speed of hay movement over the surface of the sieve

Determining the average speed of movement of stems over the surface of the sieve is also the main issue that allows determining the productivity of the separator by mass feeding and by the separated leaf part of grass.

In this case, the productivity of the separator for mass feeding is determined as follows:

$$Q_s = B \cdot h \cdot v_h \cdot \rho_h, \quad (17)$$

where B is the width of the sieve, m; h – layer thickness, m; v_h – the speed of movement of the hay layer over the surface of the sieve, m/s; ρ_h – the density of pre-crushed hay, kg/m³.

When moving a layer of pre-crushed mass over the surface of the sieve, the leaf part of the hay is separated. In this case, depending on the yield coefficient of the leaf part of hay K_s , the productivity of the separator for vitamin-grass flour is determined as follows:

$$Q_f = Q_s \cdot K_s. \quad (18)$$

The expressions (17), (18) demonstrate that to determine the performance of the separator, it is necessary to know the value of the speed of movement of the hay layer over the surface of the sieve, v_h .

The analysis of results from our theoretical studies revealed that along the first and second quarters of the circumference of the crank rotation, the hay moves along with the sieve, and when the direction of movement of the sieve changes, the mass layer moves down by inertia. At the same time, it can be assumed that the speed of hay movement over the surface of the sieve would decrease slightly. Therefore, the value of the speed of hay movement can be expressed through the average speed of the sieve itself:

$$v_h = v_{sv} \cdot K_l, \quad (19)$$

where K_l is the coefficient of hay lag from the average sieve velocity.

Fig. 4 demonstrates that the value of the speed of movement of the sieve varies equally within each quarter of the circumference of the crank rotation. Therefore, a value of the average speed of the sieve can be determined when turning the crank from 0 to $\pi/2$ and it is determined from the following formula:

$$\begin{aligned} v_{sv} &= \frac{\int_0^{\pi/2} R\omega \cdot \cos \alpha \cdot \sin \varphi d\varphi}{\frac{\pi}{2}} = \frac{2R\omega \cdot \cos \alpha}{\pi} \int_0^{\pi/2} \sin \varphi d\varphi = \\ &= \frac{2R\omega \cdot \cos \alpha}{\pi} (-\cos \varphi) \Big|_0^{\pi/2} = \frac{2R \frac{\pi n}{30} \cdot \cos \alpha}{\pi} = \frac{Rn \cdot \cos \alpha}{15}. \end{aligned} \quad (20)$$

In this case, the speed of movement of hay over the surface of the sieve can be determined as follows:

$$v_{sp} = \frac{Rn \cos \alpha \cdot K_l}{15}. \quad (21)$$

The actual value of the average speed of the sieve is determined as follows:

$$v = \frac{Rn \cos \alpha}{15} = \frac{0.015 \cdot 305 \cdot 0.9659}{15} = 0.2946 \text{ m/s}.$$

To determine the average speed of hay movement over the surface of the sieve, special experiments were carried out to determine the time of movement of the hay bundle in a known section of the sieve.

To conduct an experiment on the length of the sieve, a section of the sieve with a length of 800 mm was designated. At the same time, at the beginning of the sieve, a section of 200 mm in length was left. This section was used to accurately record the beginning of the movement of the hay bundle over the surface of the sieve. During the experiments, the drive of the leveling drum was turned off. In the process of our experiments, the separator gear motor was first started, and a bundle of hay was fed to the beginning of the sieve. When the bundle of hay reaches the mark, an electronic stopwatch is triggered on the sieve, and, at the time of reaching the hay at the end of the sieve, the stopwatch is turned off. The experiment was conducted 5 times.

The results of the experiments showed that when moving hay on a sieve section with a length of 0.8 m, the average value of the time spent was 4.2 s, that is, the average speed of hay movement $v_h = 0.19$ m/s and $K_l = 0.645$.

In this case, a formula for determining the speed of movement of hay over the surface of the sieve takes the following form:

$$v_c = \frac{0.645}{15} Rn \cdot \cos \alpha = 0.043 Rn \cdot \cos \alpha. \quad (22)$$

As a result of our theoretical research, analytical expressions were derived to determine the speed and acceleration of the sieve, as well as the equivalent forces in each quarter of the circle of crank rotation. These expressions allow determining the direction of the equidistant forces applied to the stem when moving it along the surface of the sieve within each quarter of the circumference of the crank rotation.

An analytical expression for the average speed of movement of stems over the surface of the sieve was also derived, which makes it possible to determine the value of line performance by mass feed and flour.

The rotation of the beginning of the sieve with a certain amplitude contributes to the tossing of hay in the vertical direction, that is the intensification of the process of separation of the leaf part of grass is ensured, which also proves the rationality of the selected structural and technological scheme of the separator.

5.4. Production tests of the vitamin-grass flour preparation line

To assess the work of the separator and machines of the line, production tests were carried out at the Aidarbayev peasant farm, the Enbekshikazakh region of the Almaty Oblast, the Republic of Kazakhstan.

To facilitate the work of the hay feeder operator, the line machines include a small-sized feeder-dispenser, which provides a mechanized supply of hay to the shredder designed for pre-grinding coarse forage. In this case, the capacity of

the mass feed line was equal to 953 kg/h; this capacity is the maximum for the operator who is engaged in loading the feeder-dispenser of stem feed (Fig. 10).



Fig. 10. LVM-0,4 line for preparing vitamin-grass flour, installed at the peasant farm «Aidarbayev»

With this capacity of the line for mass feeding, the yield of flour is 58.9 %, that is, the productivity of the flour line exceeds 500 kg/h [22].

At known values of the productivity, speed of hay movement, the width of sieve $b_p=0.6$ m, and a density of crushed hay of $\rho_h=125.2$ kg/m³ [15], it is possible to determine layer thickness. In this case, the thickness of the layer moved along the surface of the sieve is 0.0186 m. Observations of the separator showed that the layer thickness of less than 0.02 m ensures the rational operation of the separator.

Chemical analysis of the resulting flour showed that the carotene content in the flour was 315–337 mg/kg. In this case, according to acting standards, the carotene content in first-class flour should be up to 200 mg/kg.

The results of production tests demonstrated that the separator has high productivity and the quality of the resulting flour in terms of carotene content is 1.6 times higher compared to the acting standard. This also proves the reliability of the theoretical studies conducted and the effectiveness of the technique proposed.

6. Discussion of results of the study on the substantiation of the technological parameters for the separator of the leaf part of grass

In previous studies, the effectiveness of the use of vitamin-grass flour in feeding livestock and poultry has been proven, as it is the main carrier of carotene, protein, and minerals in the composition of mixed fodders.

Currently, most VGF production employs technical tools operated using a high-temperature drying technique. However, these VGF preparation techniques have high unit costs while the price of the units and installations used is very high. To resolve the issue related to VGF production, there is a need to devise the technique and technical tools that work at reduced unit operating costs. Therefore, a technique for preparing VGF from the leaf part of grass has been proposed and a line has been designed that operates without the use of high-temperature drying.

According to the proposed technique of preparation of vitamin-grass flour from the leaf part of grass from pre-crushed hay, its leaf part is separated. In this case, the performance of the separator depends on the speed of hay movement over the

surface of the sieve. According to the structural and technological scheme of the separator, the beginning of the sieve rotates. When the crank is rotated within each quarter of the circumference of rotation, the velocities and accelerations of the sieve change. At the same time, various forces act on the stem. Therefore, it was necessary to first determine the changes in the speed and acceleration of the sieve at full crank rotation.

To assess the performance and correctness of the choice of the structural and technological scheme of the separator of the leaf part of grass, it is necessary to determine the direction of the equivalent force at different quarters of the circumference of the crank rotation. It is known that during the operation of the separator, the direction of the equivalent force must coincide with the direction of movement of the mass. Therefore, it was necessary to determine the changes in the speed and acceleration of the sieve at full crank rotation.

Using the derived analytical expressions and the values of the optimal parameters of the separator, the actual values of the speed and acceleration of the sieve were calculated. We have built the plots of changes in the speed and acceleration of the sieve depending on the angle of rotation of the crank (Fig. 4–7). Analysis of our plots of the dependence of horizontal and vertical acceleration makes it possible to determine the direction of inertial forces. For example, Fig. 5 shows a plot of the dependence of the horizontal acceleration of the sieve on the angle of crank rotation. When one rotates the crank in the first quarter, the value of horizontal acceleration decreases from the maximum value to zero. Here, when the crank is rotated by the first 30 degrees, the acceleration reduction is carried out by 1.98 m/s², when turning to the next 30 degrees, the decrease is by 5.4 m/s², and, at the last turn of the crank, the decrease is by 7.38 m/s². That allows us to assert that when the crank is turned to the first quarter, the movement of the sieve is accompanied by braking, that is, the horizontal force of inertia is directed along the movement of the sieve.

Analysis of the vertical acceleration (Fig. 7) shows that the intensity of the acceleration increase decreases depending on the rotation of the crank. It follows that when the beginning of the sieve is raised, the movement is carried out with braking and vertical acceleration is directed upwards (Fig. 3). The analysis makes it possible to derive an analytical expression (9). Thus, we have built the analytical expressions to determine the equivalent forces in all quarters of the circle of rotation of the crank.

Next, the analytical expressions constructed helped establish the conditions for moving the stems along the inclined surface of the sieve at different quarters of the circumference of the crank rotation – formulae (10), (13), (15).

However, meeting the conditions for moving the stems over the surface of the sieve can be determined only by having the actual values of acceleration in the horizontal and vertical directions. For each quarter, the acceleration value varies from 0 to the maximum value, so there is a need to determine the average value of the acceleration rate of the sieve.

An analytical expression has been derived to determine the average value of the acceleration of the sieve, which allows determining the actual value of the equivalent force. The results of the calculation showed that when the crank rotates in three-quarters of the circle, the direction of the equivalent force coincides with the direction of movement of hay over the surface of the sieve. All this proves the reliability of the obtained optimal values for the parameters and the selected structural and technological scheme of the separator.

To determine the performance of the separator and the line, it is necessary to know the value of the speed of move-

ment of hay over the surface of the sieve. When moving the sieve towards its slope, it can be assumed that the movement of the sieve is carried out together with the hay, and, when it moves in the opposite direction, the movement of the mass decreases. Therefore, the value of the speed of movement of hay over the surface of the sieve can be expressed through the average value of the speed of movement of the sieve itself.

Based on this, an analytical expression was built to determine the average speed of movement of the sieve. As a result of our special experiments, the values of the speed of hay movement over the surface of the sieve and the coefficients of hay lag from the average speed of the sieve were determined.

As a result of our theoretical research, analytical expressions were obtained that determine the conditions for hay movement over the surface of the sieve, the values of the average speed and acceleration of the sieve. Analytical expressions for determining the speed of hay movement over the surface of the sieve, as well as the performance of the line on mass feeding and flour, have been built.

The results of our theoretical analysis demonstrated that at optimal values of the crank rotational speed, the amplitude of the oscillation, the angle of inclination of the sieve and the selected structural and technological scheme of the separator, a rational condition for hay movement over the surface of the sieve is provided.

To verify the reliability of the theoretical studies and analyze the work of the separator and all machines of the line, production tests of the line were carried out at farms.

The results from the production tests showed the rational operation of the separator and other machines of the line. The productivity of the flour line was equal to 561 kg/h. In this case, the carotene content in the resulting flour was 315–337 mg/kg.

The results of the economic analysis showed that the specific operating costs of the proposed technique and the price of the equipment used for its drying, compared with the high-temperature technique, are 6..7 times lower [22]. Thus, the use of the proposed technique and the designed line provides a solution to the problem of VGF preparation in terms of economic conditions; in other words, the tasks set have been resolved.

The review given in this paper makes it clear that VGF was earlier prepared by a high-temperature drying technique with the newer technique of drying grass with infrared irradiation. Compared to the above techniques, the proposed technique has the following advantages:

- the main drying of grass, that is to a moisture content of 30–35 %, is carried out on the swath. It is this feature of the technique that provides a sharp reduction in the specific operating costs of VGF preparation processes;

- according to the current technique, the entire biological harvest of the plant is used for the preparation of VGF. It should be noted here that one kg of alfalfa leaf contains 619 mg of carotene, one kg of the stem part – 69 mg of carotene, for clover, respectively, 525 and 25 mg of carotene [23]. If we take into consideration that the leaf part of legume grass is 40–50 %, then the stem part is, respectively, 50–60 % of the total mass of plants. According to the current technique, the maximum content of carotene in the resulting flour could amount to 289 mg/kg (the acting standard for first-class flour is 200 mg/kg). Therefore, the technique has been proposed to enable VGF production with a carotene content exceeding 300 mg/kg;

- the dried mass in the channel under the haystack is crushed in a sieve-less coarse feed shredder. At the same time, a certain leaf part of the hay is finely crushed to an average

size of 10–15 mm while the stem part is crushed into large fractions larger than 20 mm. This feature of pre-crushed hay facilitates the process of separation of the leaf part of grass.

When preparing VGF according to the proposed technique, the main limitation is the selection of hay when its moisture content reaches 30–35 %. To remove this restriction, it is necessary to mow the grass depending on the daily productivity of the line.

The choice of such a moisture content is due to the fact that during harvesting there would be no loss of the leaf part and, at this moisture content, the main moisture from the plant could be removed while the carotene losses are minimal.

When operating the line for the preparation of VGF, there is some inconvenience – manual supply of mass to the feeder-dispenser. To tackle the above disadvantage (manual mass feeding), there is a need, in the future, for research aimed at designing an improved feeder-dispenser of feed stems.

7. Conclusions

1. The result of our theoretical research has established the analytical expressions to determine the speed and acceleration of the sieve in the horizontal and vertical directions. We have built the plots of change in the speed and acceleration of the separator sieve depending on the angle of crank rotation. At the same time, the maximum values of the sieve velocity in the horizontal and vertical directions have been determined: they are the same and are equal to 0.4624 m/s, while the acceleration of the sieve in both directions is the same and is equal to 14.76 m/s².

Our analysis of the plots of the acceleration of horizontal and vertical directions makes it possible to determine directions of inertial forces in each quarter of a circle of rotation of a crank.

2. For each quarter of the circle of rotation of the crank, analytical expressions have been built to determine the equivalent force, the average value of the acceleration of the sieve, and the conditions for moving the stems over the surface of the sieve. The average acceleration of the sieve in both directions is the same and is equal to 9.42 m/s². Calculations based on the derived analytical expressions allow determining the direction of the equivalent force, that is, enable determining the conditions for the movement of stems over the surface of the sieve.

3. Analytical expressions have been derived for determining the average sieve velocity and hay movement rate over the surface of the sieve. As a result of our experimental studies, the actual value of the hay movement rate over the surface of the sieve was determined; it is equal to 0.19 m/s. At the same time, to use the derived analytical expression for determining the average speed of hay movement over the surface of the sieve, the hay lag coefficient depending on the average sieve speed was obtained; it is equal to 0.645.

4. Results from our production tests of the line showed that its productivity was equal to 953 kg/h, for flour – more than 500 kg/h. Preparation of flour from the leaf part of grass provides flour with a carotene content of 315–337 mg/kg, which proves the correctness of the selected technology for VGF preparation, as well as the structural and technological scheme of the separator, and the entire line in general.

Acknowledgments

We express our gratitude to Vladimir Golikov, Academician of the National Academy of Sciences of the Republic

of Kazakhstan; E. Naydenko, T. Smagulov, Z. Ni. They are members of the research group and have made a significant contribution to the experimental research and production tests.

The work was financed within the budget program 055 of the Ministry of Education and Science of the Republic of Kazakhstan under the project «Development of the techno-

logy and line for the preparation of vitamin-grass flour from the leaf part of grass, which ensures a reduction in specific operating costs».

We also express our gratitude to the staff of the Committee on Science of the Ministry of Education and Science of the Republic of Kazakhstan, who provided continuous funding for the project during 2012–2014.

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