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DEVELOPMENT OF A COMPACT FORAGE HARVESTER EQUIPPED WITH A STEM LENGTH ORIENTER AND RECTANGULAR DEFLECTOR FOR SMALL FARMS

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The object of the study is the technological processes of high-quality crushing of stem feeds, due to the oriented feeding of stems into the grinding chamber and transportation of the crushed mass through a rectangular deflector.

A review of the literature sources has shown that at present, the design and technological scheme of a small-sized forage harvester has not yet been developed, which in turn ensures high-quality crushing of stem feeds and reduces operating costs in small farms.

As a result of theoretical studies, analytical expressions were obtained to determine the mass velocity at the deflector outlet and the range of mass ejection in the horizontal section.

The combine productivity when mowing alfalfa was equal to 6.22 t/h, the range of mass ejection in the horizontal direction was within 7.5...8.0 m (theoretical value – 7.8 m), the average size of crushed particles was 32.89 mm (estimated length – 33.5 mm), the difference between theoretical and actual values is 1.5 %.

The results of laboratory and field tests showed the efficiency of the forage harvester, the reliability of the analytical expressions obtained and the efficiency of the stem length orienter was determined. A distinctive feature of the research results is that a design and technological scheme of a small-sized forage harvester equipped with an orienter and a theoretical description of the feed transportation process through a rectangular deflector were developed.

According to the presented design and technological scheme, the deflector and orienter have a simplified design and good quality of crushing stem feeds. All this proves the practical significance and applicability of the developed forage harvester

Keywords: forage harvester, rectangular deflector, mass ejection range, orienter, alfalfa

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1. Introduction

It is known that to increase livestock production, animals must be fed with high-quality complete feed mixtures, consisting of chopped roughage, silage, or haylage, and compound feeds. The preparation of chopped hay, haylage, and corn silage is carried out by forage harvesters.

Currently, self-propelled and trailed forage harvesters are produced in all leading countries. However, many trailed harvesters have a cutting width of about 2.0 meters. They perform corn mowing in three rows, and when harvesting chopped hay and haylage, they pick up a swath 1.2...1.3 meters wide.

Moreover, in small-sized combines, the mowed mass is fed to the cutting blade shredder by an auger. In this case, the stems in the shredding rotor chamber are arranged randomly, so the quality of their shredding does not correspond to the calculated cutting length.

Another important issue is that modern combines use deflectors with curved sections to feed the shredded mass into the body of a cart and transport vehicle. However, the mass velocity is significantly reduced in this section.

Therefore, the blades of the shredding rotor must operate at increased circumferential speeds. Here, such a deflector design ensures the loading of chopped feed into the body of a nearby tractor.

However, many farming operations cannot perform simultaneous work with three units (the first is a tractor with a combine, the second – a nearby unit, the third – a unit replacing the nearby tractor after its body is filled).

When filling a cart attached behind the forage harvester, one tractor and two carts are required, i.e. the entire job can be done with two units.

Therefore, for small farms, the development of a compact forage harvester that ensures high-quality shredding of stem feeds and preparation of silage, haylage, and chopped hay is a solution to a pressing issue in modern agriculture.

2. Literature review and problem statement

In Claas self-propelled combines, the rollers feeding the mass into the drum at different set speeds allow you to adjust the cutting length [1].

In these combines, the pre-pressing rollers orient the stems only in the vertical plane, and the location of the stems in the horizontal plane is not oriented. Therefore, it is necessary to conduct research aimed at the spatial orientation of the stems, i.e. to perform oriented feeding of stems in vertical and horizontal planes.

The paper proposes a technology for harvesting silage in polymer bags. To fill the mass into the bag, a screw press [2] is installed at the end of the deflector, but this scheme complicates the design of the machine.

According to the technology of forage harvesting, the production of feed from perennial grasses, especially legumes, should become a priority [3].

The work [4] presents the test results of the Corner Machinery Type 1300 forage harvester. The harvester was attached to a 35 kW Ursus 3512 tractor. In the field, at an average operating speed of 2.156 km/h, the combine productivity was about 7 t/h, and the mowing efficiency was 0.176 ha/h. When harvesting hay from various plants, on large family farms, the harvester showed reliable and satisfactory operation without breaking down [4].

In [5], the influence of field parameters and yields on the effective field productivity of a self-propelled forage harvester is examined.

The results were obtained when considering all fields, as well as fields with an area of more than 1 hectare were the same. Fields with an area of less than 1 hectare showed the worst results [5].

The unresolved problem remains the high energy consumption of forage harvesters, which are inexpedient to use in small farms.

These results show that currently farms have fields with an area of 1...5 hectares. It is for such farms that there is a need to develop a small-sized combine harvester providing stocks of silage, haylage and crushed hay.

Two pairs of toothed rollers rotating at different speeds have been developed for grinding corn silage. It was found that fine-grained particles (less than 9 mm) were well siloed with pH values from 3.8 to 4.1 [6].

The work [7] provides information on determining the mass flow rate in the chopper chamber, the impact force at various cornstalks and the torque acting on the driveshaft of the drive mechanism. The paper substantiates the main parameters of the forage harvester.

In [8], the results of experimental studies are presented to determine the specific energy consumption of the forage harvester accelerator and the force generated by the flow of raw materials on the cutting stem mass catcher board. The influence of the circumferential velocity of the accelerator rotor blade ends, the number of blades, the angle of inclination of the blades to the radial direction, the gap between the casing and the blade ends was studied. The dependences of the specific energy consumption for accelerating the cut mass and the force on the catch shield on the studied factors are obtained – regression equations in the form of second-order polynomials [8]. The paper considers the acceleration of the flow as it moves along a curved deflector. However, the work does not propose a specific solution for accelerating the flow during its movement in curved deflectors.

In [9], equations of motion of the crushed mass to the side walls of the trapezoidal and curved sections of the deflector are obtained. The paper considers the process of transporting the crushed mass through a deflector having a curved section.

As a result of theoretical and experimental studies, the process of mass transportation in various deflector sections was determined, and some operating modes of the forage harvester were justified, taking into account the efficiency of the mass transportation process through the deflector.

The paper considers the issues of mass transportation along a curved deflector. However, when the mass moves along a curved deflector, a centrifugal force appears, contributing to a significant increase in friction force. Therefore, it becomes necessary to conduct research on developing new ways of transporting mass into the body of a vehicle.

In [10], an overview of the design of equipment and technology for crushing feed materials is made. The paper discusses various ways of grinding feed raw materials. However, the issue of adjusting the size of the crushed particles is also not considered in this work.

Analytical expressions were obtained to determine the average length of pre-crushed feed particles, depending on the distance between the faces of adjacent knife working bodies, i.e. from the step of their placement in rows [11]. At the same time, hammers with cutting edges grind the wet mass, as well as create an airflow and work as a flow accelerator at high speed.

The paper considers the issue of adjusting the size of the crushed particles depending on the pitch of the hammers. However, this is not suitable for forage harvesters. Here, radially and horizontally positioned knives interact with anti-cutting knives, i.e. the grinding methods differ.

As a result of theoretical studies, an analytical solution was obtained to determine the velocity of feed mass movement along the circular section of the deflector, and when the feed moved along this section, the velocity decreased by 2.47 times [12].

The work presents the results of research on the processes of mass transportation along a curved deflector. However, the paper does not propose a way to reduce the friction force that appears in the curved sections of deflectors.

In [13], the process of grinding the feed mass by a screw working body with knives and a leveling device, which accelerates the grinding and mixing processes, is considered.

The paper discusses the processes of grinding feed raw materials by a screw working body. Here, the issue of adjusting the size of the crushed particles is not examined.

The work provides an analytical expression for determining the average length of crushed particles using methods of probability theory [14].

In the KSK-600 forage harvester, the maximum calculated cutting length is within 25...50 mm, when the number of knives on the grinding drum changes from 12 to 6 pieces [15].

The paper [16] presents the results of laboratory and field tests of the RSM-2650 self-propelled forage harvester. At the same time, the combine throughput during corn harvesting was in the range of 34.2...51.9 kg/s and the mass fraction of crushed particles up to 30 mm was 91...96 %. However, the height of the cut stems was 250 mm. At this cut rate, crop losses amount to more than 5 %.

Forage harvesters with a rotary chopping and throwing apparatus do not allow harvesting herbs for haylage with a mass fraction of 8–19 mm particles in the range from 45 % to 65–75 %, combines with a double grinding apparatus provide this opportunity only when adjusting the angular velocity of the auger and (or) a disk or cylindrical drum. A double shredder meets the requirements for the quality of grinding different feeds, if the angular velocity of the screw and (or) a disk or cylindrical drum is regulated [17]. Here, with a radial knife, the beveled, pre-crushed mass is fed by an auger to the shredder. When fed by an auger, the stems are distributed randomly. In this case, the average length of the crushed particles does not correspond to the calculated average cutting length of the feed.

The analysis of the studies showed that currently deflectors with rectilinear and curved sections are used for mass transportation. However, when the wet mass moves on these curved sections, a centrifugal force acts, creating a significant friction force. This reduces the rate of mass ejection from the deflector. Therefore, special flow accelerators are used in high-performance combines; in small-sized machines, using a flow accelerator increases the cost and complicates the design of the combine.

The review also showed that pre-pressing rollers are used in modern forage harvesters. However, they ensure the orientation of the stems only along the vertical plane, and we have not found any research papers considering the processes of spatial orientation of the stems at the entrance to the grinding chamber.

In modern combines, cutting drums with different numbers of knives are used to improve the quality of crushed grain feeds. However, this complicates the design of forage harvesters.

Therefore, in order to significantly improve the quality of the crushed particles, we propose to perform the process of spatial orientation of the stems at the entrance to the grinding chamber. This is a solution to an urgent problem in creating modern forage harvesters.

In addition, trailed combines that supply stem feeds to the cutting device with an auger do not ensure the production of fine particles that meet zootechnical requirements.

It is known from the review of literature sources that researchers pay considerable attention to the quality of chopped forage in forage harvesters. This issue in self-propelled combines is solved by adjusting the number of knives in the chopping drum and installing this chopping device. The review does not find a solution to the issue of high-quality chopping of stem forage in small-sized forage harvesters. This is because in many cases, researchers try not to complicate the design of a small-sized machine.

However, it is clear here that the quality of chopped forage is of great importance. Moreover, for harvesting haylage and silage, the main part of the chopped forage should be up to 30 mm in size.

In small-sized forage harvesters, the issue of transporting chopped forage is also crucial. This problem of modern forage harvesters is solved with a curvilinear deflector device. This deflector design is appropriate for high-performance combines. In addition, researchers found that when the mass moves along the curved section of the deflector, the mass velocity decreases. Therefore, a special flow accelerator is installed in high-performance machines.

In farm conditions, organizing the work of a combine with several units, consisting in the transportation of chopped mass, also has a certain complexity.

All this suggests that it is advisable to conduct a study on developing a compact forage harvester that ensures high-quality chopping of stem fodder and transportation of chopped mass with reduced resistance.

3. The aim and objectives of the study

The aim of the study is to develop a compact forage harvester equipped with a stem length orienter and rectangular deflector, ensuring the preparation of stem feeds with reduced operating costs and improved quality indicators in the conditions of small farms.

To achieve the aim, the following objectives were set:

– to substantiate the design and technological scheme of a small-sized forage harvester for farms;

– to determine the speed of feed mass movement through the rectangular deflector;

– to determine the range of the feed mass after exiting the deflector;

– to conduct laboratory-field tests to verify the rational kinematic modes of operation of the stem length orienter and rectangular deflector of the combine, as well as to determine the accuracy of theoretical studies.

4. Materials and methods

The object of the study is the technological processes of spatial orientation of stems when entering the chopping rotor chamber and transportation of chopped feed along a rectangular deflector and in an open air environment.

When studying the process of stem orientation, the proposed hypothesis is that if there is orientation of stems, then the average size of the chopped particles should coincide with the calculated length of the stem feed.

When transporting the chopped mass, the range of mass ejection is assumed to be 1.3...1.5 times greater than the distance from the deflector end to the tailboard of the vehicle.

In the calculation and testing processes, when determining the mass flight range, the process of mowing and chopping alfalfa was selected, assuming that this process is more indicative when determining the range of mass ejection from the deflector.

A simplification given in the calculation is that in theoretical studies, when considering the forage mass velocity, the velocity of the airflow created by the chopping rotor blade is not taken into account. In this case, we assume that during operation, the deflector volume is filled with the transported mass and here the influence of airflow velocity is insignificant.

In substantiating the design and technological scheme of the compact forage harvester to eliminate the shortcomings of existing machines, a new orienter and rectangular deflector were proposed.

Previous research, using methods of theoretical mechanics, found that the movement of moist corn mass through a circular section of the deflector results in a 2.47-fold reduction in the feed velocity [12]. The results of these studies provide a basis for proposing a rectangular deflector shape in the compact forage harvester.

Methods of solving problems of mathematics are used in theoretical studies.

In this case, the grinding rotor blades emit a mass of feed at a certain velocity. The result of the blade action is taken into account with the circumferential velocity at the blade ends.

When moving the feed through the deflector, the forces of the feed weight and airflow resistance are taken into account. Applying methods for solving problems of dynamics, equations of feed motion along the trajectory of the O_x coordinate axis were compiled.

Laboratory and field tests of the forage harvester were carried out according to GOST 28722-2018 "Agricultural machinery. Mowers and mower conditioners. Test methods". When tested according to this GOST, the combine productivity was determined. To do this, the electronic stopwatch determines the time of movement of the unit by 50 meters with the ADC/1R-0.5/1I-2 electronic dynamometer (50.0–500.0 N), the weight of the feed in the cart body is determined. Samples for operation were selected at 5 points of the body, i.e. at the corners and in the center of the side of the trolley. To determine the value of this mass ejection, video recordings of the ejected feed from the deflector were carried out.

The experiments were conducted from 24 to 28 May 2024. The moisture content of alfalfa during the first mowing was 82.45 %. The sampling was carried out manually. Lines corresponding to different classes of cutting lengths of crushed particles were applied on the A1 sheet. At the same time, there is an error in determining the length of the crushed particles equal to 0.1 mm. Three samples were analyzed to determine the average length of the crushed particles. To adjust the sample weight, an MW-II-3000 laboratory scale (manufactured by CAS Corporation, South Korea) with a certified division value of 0.1 g was used.

Experiments to determine the combine productivity were carried out at unit speeds of 0.74 m/s (reduced first speed of the MTZ-82 tractor). At the same time, the combine overcame 50 m of the length of the pen in 67.57 s. In this case, the mowed weight was 116.75 kg, i.e. the combine productivity was 6.22 t/h.

Three samples were analyzed to determine the average size of the crushed particles. The average length of the crushed particles was 32.89 mm. The average square deviation was 0.85 mm. This shows a small deviation of the average size of the crushed particles in each sample from the average cutting length for three samples.

In this case, such a careful determination of the average size of the crushed particles is given to determine the reliability of theoretical studies.

5. Efficiency of a small-sized forage harvester with an orienter and rectangular deflector

5. 1. Substantiation of the design and technological scheme of a compact forage harvester

Modern forage harvesters are equipped with deflectors that have vertical and curved sections. The choice of such a deflector design is due to the fact that it facilitates the loading of chopped feeds into the body of a trailer attached to the harvester and a nearby transport vehicle. However, this deflector design has a significant drawback; when the moist mass moves through the curved section, substantial centrifugal force and friction force appear, which slows down the moving mass flow.

To overcome this resistance force, high-performance combines are equipped with special flow accelerators, and in machines equipped with blade chopping rotors, their circumferential speed at the blade ends should be within 40–45 m/s.

However, for the cutting working body, the optimal circumferential speed of the blades should be within 30–35 m/s [3, 7]. In designs equipped with blade chopping devices, and in similar combines, an elevated speed of knives and blades is set to ensure sufficient flow speed, i.e., to overcome the resistance force of the mass through the curved section of the deflector.

If we consider that the speed of mass movement on the curved section of the deflector will be approximately 20 m/s and at a radius of curvature of 1.25 m, then the value of the centrifugal force is 30 times greater than the force of the weight of the moving mass through the curved section of the deflector. Therefore, for a compact combine, eliminating this friction force reduces the speed of the knife and blade, i.e. reduces the energy intensity of the processes of chopping and transporting feed through the deflector.

In many cases, compact combines must produce silage for farms with up to 100 head of cattle. For such a farm, the total volume of silage to be harvested is 300–350 tons, and this silage volume can be obtained from harvesting an area of 4.0–4.5 hectares of cornfield.

If the compact combine will perform mowing and chopping of corn stalks arranged in two rows, then the combine productivity will be 0.55–0.6 hectares per hour, i.e., such a combine can produce the necessary volume of work in 1.5 shifts. In this case, there is no need for the farmer to use three units simultaneously during the combine's operation.

Therefore, compact combines must load chopped feeds into the body of a trailer attached to the combine frame. With such a combine operation, it is reasonable to use a deflector that has a rectangular shape and is positioned at a certain angle towards the trailer (Fig. 1).

According to the described scheme, the rectangular deflector will not experience the centrifugal force that occurs when the mass moves through a curved section of the deflector. When the mass is ejected, there is a significant reduction in resistance from the gravitational force of the mass.

In this case, coupling the combine with another trailer can be done as follows: After filling the trailer, the unit reverses about 5 to 7 meters, and the trailer hitch should be detached. The tractor with the combine then moves out to an open field. Another tractor brings a free trailer to the rear of the combine and positions the trailer perpendicular to the combine.

In this process, the second tractor driver performs the coupling of the free trailer with the combine and attachment of the hitch of the filled trailer. The aforementioned tasks are completed within 2 to 3 minutes.

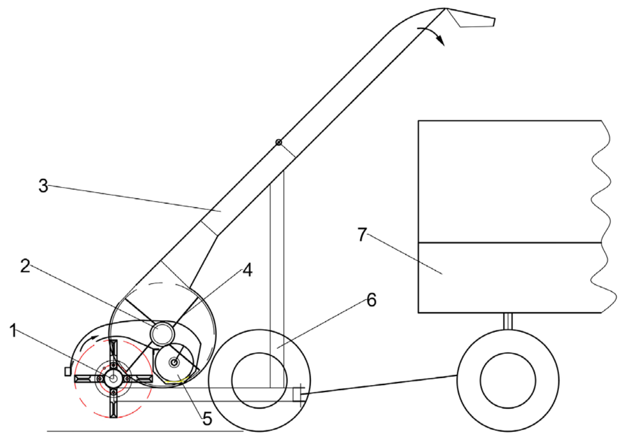

Fig. 1. Design and technological scheme of a forage harvester with a rectangular deflector: 1 – rolling rotor; 2 – chopping rotor; 3 – deflector; 4 – knife with blade; 5 – auger; 6 – wheel; 7 – trailer

Furthermore, according to another scheme, to enable continuous operation of the combine, it is necessary that at least two units work with it.

Many small farms do not have three tractors, so developing a combine with a rectangular deflector has practical significance.

To improve the quality of chopped stem feeds, we have proposed a hypothesis ensuring that the mass enters the chopping rotor chamber strictly according to the length of the stems by compressing the fed mass into the chopping chamber in both horizontal and vertical directions, and the adjustment of the cutting length is achieved by changing the stem feed velocity and the number of knives installed on the rotor, which also enhances the quality of chopped stem feeds. At the end of the cantilever auger, a compressing cylindrical drum is installed, which is equipped with angular plates at the edges, having an inclination relative to the end face and the rotation direction of the drum, and the angle of inclination between the plate and the generating cylindrical surface of the drum should be greater than the angle of friction between the steel surface and the feed materials (Fig. 2, 3).

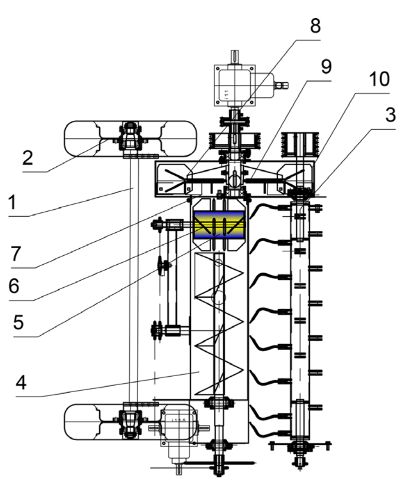

Fig. 2. Design and technological scheme of the combine: 1 – rolling rotor; 2 – chopping rotor; 3 – mowing rotor; 4 – cantilever auger; 5 – compressing drum; 6 – angular plates; 7 – counter-cutting plate; 8 – knife; 9 – chopping rotor; 10 – deflector

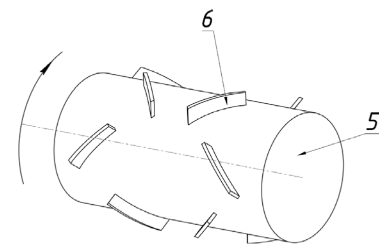

Fig. 3. General view of the orienting drum: 5 – compressing drum; 6 – angular plates

When the orienter is functioning effectively, the average length of the chopped stem feeds should match the calculated cutting length. Thus, a design and technological scheme of a combine was developed, equipped with an orienter that ensures oriented feeding into the chopping rotor chamber strictly by the length of the stems.

For mowing and chopping grass or corn for silage, the combine's drive mechanisms are engaged, and the unit moves across the field. In this process, the green grass or corn stalks are mowed and preliminarily chopped by the mowing rotor (3). The preliminarily chopped mass then enters the trough of the cantilever auger (4), and the auger blades feed the mass to the compressing drum (5). The drum (5) compacts the mass in the vertical direction. In the compacted layer, the stems will be arranged in a horizontal plane; in this case, the angular plates (6) move the mass towards the center of the drum, i.e. the mass is compacted in both horizontal and vertical directions, ensuring the orientation of the stems strictly by length. As a result, the feed stems enter the chopping chamber almost perpendicular to the counter-cutting plate (7) and in this case, the stems, getting between the counter-cutting plate (7) and the knife (8) of the chopping rotor (9), are cut to the same size. Then, the chopped mass is fed by the blades of the chopping rotor (9) through the deflector (10) into the body of the transport vehicle. During the combine operation, the cutting length of the harvested feeds is adjusted depending on the rotation speed of the compressing drum and the number of knives on the chopping rotor.

Thus, the design and technological scheme of a forage harvester equipped with a stem length orienter and rectangular deflector is substantiated.

5. 2. Determination of feed mass velocity through a rectangular baffle

When the combine operates, the mowed mass is conveyed through the auger into the chopping rotor chamber. In this case, a specific piece of the moving layer is cut by the radial knives of the chopping rotor with the mass *m*. It is then ejected through the rotor blades into the deflector tube (Fig. 4).

When the mass *m* is ejected, it moves in a straight line through the deflector, i.e. at an angle α to the horizontal axis *x*. It is clear here that air resistance always acts against the velocity of the mass *m*.

Therefore, the sum of the acting forces is determined by the formula:

$$\sum F_a = -P\sin a - R = -P\sin a - \frac{c_x \rho S v_a^2}{2}, \quad (1)$$

where P – gravity force of the mass m, N; R – air resistance force, N; c_x – mass drag coefficient; ρ – air density, kg/m^3; S – area of the particle projection on the plane perpendicular to the particle motion direction, m^2; v_α – velocity of the ejected feed or airflow impinging on it, m/s.

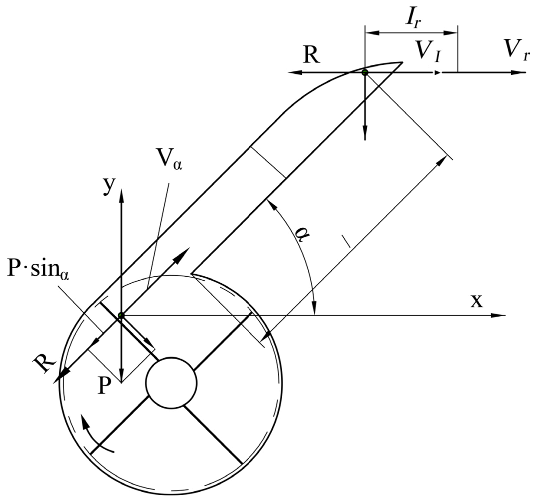

Fig. 4. Diagram of mass movement through the deflector

Let us formulate a differential equation for the rectilinear motion of the feed having mass m, velocity v_a and along the path l_a:

$$m\frac{v_a dv_\alpha}{dl_\alpha} = -P\sin\alpha - \frac{c\rho S v_a^2}{2}. \qquad (2)$$

Expressing the feed mass through gravity and both parts of the differential equation multiplied by 2, we get:

$$\frac{2\rho\sin\alpha}{g} v_\alpha \frac{dv_\alpha}{dl_\alpha} = -2\rho\sin\alpha - c_x\rho S v_\alpha^2. \qquad (3)$$

Dividing both parts of the equation by the multiplier $c_x\rho S$, we get:

$$\frac{2\rho\sin\alpha}{c_x\rho S}\cdot\frac{1}{q}\cdot v_\alpha\frac{dv_\alpha}{dl_\alpha} = -\frac{2\rho\sin\alpha}{c\rho S} - v_\alpha^2.$$

Let's introduce the notations: $\frac{2\rho\sin\alpha}{c_x\rho S} = a^2$, then the equation will take the form:

$$\frac{a^2}{q}\cdot v_\alpha\frac{dv_\alpha}{dl_\alpha} = -\left(a^2 + v_\alpha^2\right). \qquad (4)$$

Dividing the variables, we get:

$$\frac{v_a dv_\alpha}{a^2 + v_\alpha^2} = -\frac{q}{a^2} dl_\alpha. \qquad (5)$$

To determine the velocity of the ejected mass at the end of the deflector, we define the limits of integration by the velocity and path of mass movement. Here, for the velocity of the ejected mass, the initial velocity will be equal to the knife speed v_H, and the mass velocity at the end of the deflector is denoted by v_l. Along the path of mass movement, at the beginning l_α=0, and at the end, it equals the deflector length, i.e. l_α=l. By these specified limits of velocity and path of mass movement, we perform the integration of the equation, multiplying both sides of the equation by 2, we obtain in the numerator – the integrand function will be equal to the derivative of the denominator, i.e. the solution of the function looks as follows:

$$\int_{v_H}^{v_l}\frac{2v_a}{a^2+v_a^2}\mathrm{d}v_a = -\frac{2q}{a^2}\int_0^l \mathrm{d}l_a,$$

$$\ln\left(a^2+v_a^2\right)\Big|_{v_H}^{v_l} = -\frac{2q}{a^2}\left(l_a\right)\Big|_0^l,$$

$$\ln\left(a^2+v_l\right) - \ln\left(a^2+v_H^2\right) = -\frac{2q}{a^2}l,$$

$$\ln\frac{a^2+v_l}{a^2+v_H^2} = -\frac{2ql}{a^2},$$

$$\frac{a^2+v_l^2}{a^2+v_H^2} = e^{-\frac{2ql}{a^2}}.$$

From here, we finally obtain the formula for determining the mass velocity at the end of the deflector:

$$v_l = \sqrt{e^{-\frac{2ql}{a^2}}\left(a^2+v_H\right) - a^2} = \sqrt{\frac{1}{e^{\frac{2ql}{a^2}}}\left(a^2+v_H^2\right) - a^2}. \qquad (6)$$

Thus, an analytical expression was obtained for determining the velocity of the ejected mass at the deflector outlet.

5. 3. Determination of the flight range of the ejected feed mass after its exit from the deflector

During the harvester operation, the mass coming out of the deflector must reach the rear side of the cart. Let us denote the mass velocity at the end of the path l_r by v_r (Fig. 4).

If the length of the trailer side is 4.0 m, then l_r 6...8 m, the final mass velocity should be equal to the fluttering speed of the moist stem mass. The fluttering speed of stem and grain feeds ranges from 5.0 to 10.8 m/s [18]. Considering that the fluttering speed of moist stem feeds is important, we will take the final feed mass velocity at the end of the path l_r, v_r 8.0 m/s. This choice is related to the fact that if the mass velocity is less than the fluttering speed, the heavy moist mass will fall downwards, i.e. the mass movement in the horizontal direction will cease. Therefore, for optimal loading of feeds into the trailer body, the mass velocity at the beginning (v_l) and at the end of the path (v_r) must have a specific value, and obtaining an analytical expression to determine the value of the path of mass movement is the solution to the pressing task of harvesting stem feeds.

To solve this task, we will apply the methods of solving the main problem of dynamics during the rectilinear motion of chopped particles and compile a differential equation of the following form:

$$mv_x\frac{dv_x}{dx} = \sum F_{KX}, \qquad (7)$$

where m – mass of the ejected particle, kg; v_x – horizontal velocity of the ejected particle, m/s; ΣF_{KX} – total force acting on the particles along the x-axis.

In this case, the air resistance force F_B and the gravity force act on the particles in the horizontal direction.

Calculating the projections of the acting forces on the x-axis, we find that [19]:

$$\sum F_{KX} = F_B = \frac{c\rho S v_E^2}{2}. \qquad (8)$$

To determine the pattern of mass movement on a straight section, let's formulate a differential equation, noting that in this case the particle velocity and the airflow velocity have the same value and are equal to v_x:

$$mv_x \frac{dv_x}{dx} = -\frac{c\rho S v_x^2}{2}. \tag{9}$$

After separating the variables:

$$m\frac{v_x dv_x}{v_x^2} = -\frac{c\rho S}{2}dx.$$

$$\frac{v_x dv_x}{v_x^2} = -\frac{c\rho S}{2m}dx. \tag{10}$$

To solve the problem, it is necessary to determine the limits of integration. For the mass velocity, the initial velocity is v_l and the final particle velocity is v_r. In formula (10), x represents the path length of the ejected mass, therefore the lower limit is $x=0$, and the upper necessary path length is l_r.

Now, by integrating the equations (10), we obtain:

$$\int_{v_l}^{v_3} \frac{v_x dv_x}{v_x^2} = -\frac{c\rho S}{2m}\int_0^{l_3} \mathrm{d}x.$$

$$\frac{1}{2}\int_{v_l}^{v_3} \frac{2v_x dv_x}{v_x^2} = -\frac{c_x\rho S}{2m}\int_0^{l_3} \mathrm{d}x,$$

$$\ln\left(v_x^2\right)\Big|_{v_l}^{v_r} = -\frac{c_x\rho S}{m}(x)\Big|_0^{l_r} = \ln v_r^2 - \ln v_l^2 = -\frac{c_x\rho S}{m}l_r,$$

$$\frac{c_x\rho S}{m}l_r = -\left(\ln v_r^2 - \ln v_l^2\right) = \ln v_l^2 - \ln v_r^2 = \ln\frac{v_l^2}{v_r^2},$$

$$l_r = \frac{m}{c_x\rho S}\cdot\ln\frac{v_l^2}{v_r^2}. \tag{11}$$

Thus, an analytical expression was obtained for determining the flight range of the chopped mass from the physico-mechanical indicators of the feed and the proposed velocity v_r, set at the end of the feed mass flight, i.e. for example, the mass velocity near the rear wall of the trailer.

5. 4. Tests to verify kinematic modes and confirm the reliability of theoretical studies

The development of a compact forage harvester is carried out under the grant funding program for project No. AR19676816 by the Ministry of Science and Higher Education of the Republic of Kazakhstan.

In 2023, as per the project plan, the design documentation was developed and a prototype model of the combine was manufactured.

Currently, laboratory-research tests of the combine have been conducted under the conditions of the Aidarbayev E peasant farm in the Enbekshikazakh district, Almaty region. The test was conducted during the mowing and chopping of alfalfa. The alfalfa yield was 1.73 kg/m^3.

During the tests, the PTO rotation speed of the tractor was set to 850 rpm. This is because the combine is equipped with a rectangular deflector, which provides unloading of feed without involving centrifugal force. Therefore, a medium operating mode of the combine mechanisms was selected. Depending on this chopping rotor speed, the auger speed is 306 rpm, and the orienting drum – 170 rpm. In these kinematic modes, the feed speed of the auger was 1.66 m/s, and the feed speed of the mass by the orienting drum was 2.847 m/s. The width of the combine's capture was 1.35 m, and the speed of the unit was 0.74 m/s.

In this case, the selection of kinematic modes for the combine was such that with an average chopping rotor speed (n_p=850 rpm), the feed speed of the auger was 1.7 to 2.0 times greater than the speed of the unit, and the feed speed of the mass by the orienting drum into the chopping rotor chamber was 1.7 times greater compared to the feed speed of the mass by the auger.

With this speed, the combine productivity in mowing and chopping alfalfa was 1.728 kg/s=6.22 t/h.

To determine the reliability of the conducted theoretical studies, it was necessary to determine the weight of the mass cut by one knife and the feed velocity at the deflector outlet, as well as the length of the mass's flight after it exits the deflector.

In this case, the auger length was 0.825 m and at its speed of 1.66 m/s, it ensured the delivery of mass to the orienting drum in 0.5 seconds, i.e.; during this time, the auger delivers 0.865 kg of mass to the orienting drum.

The drum surface accommodates orienting blades and two rows of fingers for accelerated mass delivery to the chopping rotor chamber. As noted earlier, 0.865 kg of chopped alfalfa enters the auger chamber, and with an auger length of 0.825 m, this mass inside the auger chamber is distributed at 1.048 kg/m.

During the time it takes for a row of the orienting drum fingers to approach, the auger moves the mass by a length of 0.293 m.

For this length of the delivered mass, the orienting drum receives 0.307 kg of mass.

Assuming that the fingers of the orienting drum (diameter of the orienting drum – 0.32 m) make the delivery at an arc length of 0.335 m and a mass of 0.307 kg, the specific mass was 0.9169 kg/m. At a drum speed of 2.847 m/s, it covers this length during the mass delivery to the chopping rotor chamber in 0.1176 seconds. With a chopping rotor speed of 850 rpm and the number of knives at 6, the approach time for one knife is 0.01176 s, i.e. during this time, from the feed of length 0.335 m and mass 0.307 kg, the knife separates 0.0307 kg of chopped alfalfa, and the cutting length is 0.0335 m.

The chopped wet alfalfa weighing 30.7 g was located on a rectangle of length 90 mm and width 59 mm, i.e. S=0.00531 m^2.

Calculations using formula (6) showed that the mass velocity at the deflector outlet was 20.85 m/s, and the mass ejection range was 7.8 m [19].

In calculating the range of mass ejection from the deflector using formula (11), it was taken into account that the mass velocity at the deflector outlet was 20.85 m/s, and the mass velocity upon hitting the ground surface was about 8.0 m/s, which is the average fluttering speed, as the fluttering speed of many materials is in the range of 5...10 m/s [18].

The test results showed that the actual mass ejection range was within 7.5 to 8.0 meters, indicating the reliability of the obtained analytical expressions.

Another important innovation in the design and technological scheme of the forage harvester is the presence of a guiding drum (Fig. 5).

During the tests, the orienting drum performed its function flawlessly. Observations of the drum operation showed that after operation, both the auger chamber and the orienting drum were in a clean state, thereby proving that the orienting drum consistently delivered the mass to the chopping rotor chamber without failure. The calculated cutting length was 33.5 mm.

Fig. 5. General view of the auger with a guiding drum

To determine the actual average length of the chopped particles, the samples obtained were analyzed by mass and cutting length. During the analysis of the samples, a significant portion of the mass, sized 0 to 5 mm, consisted of the leafy part of alfalfa. Therefore, this leafy part was excluded and was not used to determine the average length of the chopped particles.

For clarity, we present the analysis results of one sample (Table 1).

Table 1

Results of the analysis of crushed alfalfa

No.	Class, cutting length, mm	Mass, g	Mass fraction, %	$l=(l_a \cdot P)/100$
1	5–10	6.2	18.34	1.38
2	10–20	5.2	15.38	2.31
3	20–30	6.2	18.34	4.59
4	30–50	9.5	28.11	11.24
5	50–60	2.6	7.69	4.23
6	60–80	2.5	7.4	5.18
7	80–100	1.1	3.25	2.93
8	100–120	0.5	1.48	1.63
Total		33.8	100 %	33.49

The analysis of the samples showed that the average size of the chopped particles was 33.49 mm. Here, the average size of chopped particles from the three analyzed samples was 32.89 mm. The calculated average size of chopped particles is known to be 33.5 mm. The difference between the calculated and actual values of the average size of chopped particles is only 1.85 %. This proves the orienter effectiveness. In all samples, the mass fraction of chopped particles up to 50 mm constitutes over 80 %, which meets the requirements for preparing green mass and harvesting silage.

6. Discussion of research on the compact forage harvester's design and parameters

Fig. 1 shows the design and technological scheme of a small-sized forage harvester. The main difference between this scheme and the existing ones is that it is proposed to install a rectangular deflector and orienter in the harvester, ensuring that the mass enters the chopping rotor chamber along the length of the stems. Here, in previous studies, it is known that in a curved deflector, the mass velocity decreases by 2.47 times [12], and in a rectangular deflector – by 1.68 times, which proves the advantages of a rectangular deflector. The inclusion of an orienter in the harvester design ensures high-quality chopping of stem fodder when harvesting haylage and silage. This is proven by the results of testing the forage harvester.

Fig. 2 shows the general structure of the forage harvester and orienter, demonstrating that the developed harvester has a simple design. This combine design provides high-quality preparation of silage, haylage and chopped hay by two units, which is rational in farm conditions.

As a result of theoretical studies, analytical expressions were obtained for determining the forage mass velocity at the outlet of the deflector (6) and the range of mass ejection from the deflector (11).

These analytical expressions include the main physical and mechanical properties of forage materials, parameters and kinematic modes of the combine, i.e. the obtained expression is a mathematical model of the process of transporting forages in a rectangular deflector.

Substituting the values of the physical and mechanical indicators of the forage, parameters and kinematic modes of the machine, the values of the mass velocity at the deflector outlet and mass ejection range are determined. At the same time, according to the mass ejection data, their theoretical and experimental values coincide with each other. This shows the reliability of the theoretical studies conducted.

Table 1 shows the results of the sample analysis, i.e. the quality indicators of chopped alfalfa.

In this case, the calculated and actual values of the average size of the chopped particles are very close, the difference between them is 1.85 %. This also shows the orienter efficiency.

Hence, it is clear that the developed forage harvester ensures high-quality harvesting of stem feed in farm conditions. At the same time, the harvester carries out the processes of harvesting stem feed in farm conditions, in rational kinematic and technological modes.

An analysis of the design of modern forage harvesters shows that radial and drum knives with anti-cutting plates are used for high-quality crushing of wet mass [1, 2]. Screw working bodies with knives are used for grinding feed materials [14, 20].

However, the working bodies used in stationary machines are not applicable for forage harvesters that provide mowing and grinding of grass and corn of milky-waxy ripeness.

In the design of the compact forage harvester, the main difference from existing models is the presence of a rectangular deflector and orienter, which ensures the mass entry into the chopping rotor chamber by the length of the stems. The need for a rectangular deflector is explained by the fact that for harvesting stem feeds in small farms, the simultaneous use of three units is very costly and often not possible, as many small farms do not have three tractors available.

Furthermore, the use of a rectangular deflector facilitates the transport of the chopped mass through the deflector tube, eliminating the influence of centrifugal force. All this also ensures that the combine operates at medium PTO speeds of the tractor.

Researchers have been engaged in the process of oriented submission for a long time. There may be applications of roller drums when feeding wet mass to the cutting drum [11, 13]. Studies have also found that the quality of grinding depends not only on the properties of feed materials and on the design of machines and working bodies [21]. However, these works do not propose a device providing spatial orientation of stems for a forage harvester.

The presence of an orienting drum in the combine's design helps improve the quality of the chopped stem feeds. The drum orients the stems in a vertical plane, and the drum's blades create a horizontal movement of the stems towards the center of the drum. Thus, the orienting drum facilitates the orientation of the stems in both vertical and horizontal planes. The orienter effectiveness is evidenced by the matching of the calculated average size of the chopped particles to the actual values of the average size. It should also be noted that the mass fraction of particles up to 50 mm is over 80 %, which also proves the effectiveness of the orienting drum.

The results of theoretical research allow determining the mass velocity at the deflector outlet and the range of mass flight after exiting the deflector. This makes it possible to select the operating mode of the chopping rotor and determine the rational speed of mass ejection from the deflector. The calculated mass outlet velocity was 20.85 m/s, and the mass flight range was 7.8 m.

The test results showed that the mass ejection range was within 7.5 to 8.0 m, therefore, the theoretical and actual values of the mass flight range coincide, proving the reliability of the theoretical studies.

In fact, this mass outlet velocity value provides rational mass distribution in the trailer body. The mass flying after flight over the trailer body begins to decrease in altitude, i.e. this velocity is sufficient for effective loading of the trailer body. This also indicates the rationality of the kinematic modes of the chopping rotor and the deflector shape. At a higher rotor speed, the mass ejection range would increase, which is undesirable.

The proposed deflector shape and similar theoretical studies were not found by us in previous works. Furthermore, previous studies on the transport of chopped mass through the deflector have considered parameter justification for curved deflectors [9, 22]. Therefore, research aimed at justifying the kinematic parameters of the process of transporting chopped mass through a rectangular deflector is of current relevance in the development of compact forage harvesters.

In [23], the nature of feed mass movement in the curved deflector of the forage harvester was determined. At the same time, it was found that particle movement in the deflector has two stages. At the first stage, the particles move discretely, and at the second stage, after a collision with the upper wall of the deflector, the flow of crushed feed becomes dense, i.e. after passing through the mass on the curved section of the deflector, the flow is slowed down and it moves in a continuous stream.

Video recordings of the mass exiting the rectangular deflector show that the feed mass does not move in a dense layer, but not in a connected flow. In this case, the ejected mass of each blade moves without friction separately, which shows the advantage of a rectangular deflector.

The conducted theoretical studies are primarily used to justify the kinematic modes of mass transport processes within the rectangular deflector. Therefore, the main limitation of the obtained analytical expression (6) is that it is used to justify the kinematic modes of the rectangular deflector.

The obtained formula (11) can be applied to all types of deflectors. As a result of special experimental studies, the values of velocity v_r for other feed types can be refined by changing the v_r values depending on the moisture content of the feeds.

From this, it follows that reducing the knife and blade speed ensures a decrease in the power consumed, i.e. a decrease in the energy intensity of the processes of chopping and transporting the mass through the deflector.

It should also be noted that as the feed mass changes, so does the cross-sectional area of the feed. Therefore, the obtained expressions adequately describe the mass transportation process at various combine capacities. Thus, the analytical expressions obtained are intended to determine the linear speed of the knife and rational modes of the process of transporting chopped feeds through the rectangular deflector of the forage harvester.

A limitation of this study is that the velocity of the airflow created by the chopping rotor was not considered when the mass moves through the deflector tube. However, the machine design includes blades that provide mass ejection through the deflector. At this stage, the airflow velocity is approximately three times less than the linear speed of the knife and blades.

Therefore, the initial theoretical research was conducted without considering the airflow velocity. Further development of the research can be conducted taking into account the airflow velocity.

However, during the mowing and chopping process, the amount of air entering the chopping chamber significantly reduces, and this decreases the airflow velocity in the deflector tube. Therefore, at this stage of theoretical research, this process factor was not accounted for.

The test results showed that the forage harvester operated at an average PTO rotation speed of the tractor. This is sufficient rationality in the developed design and technological scheme and indicates the effectiveness of the rectangular deflector and the orienting drum. The accuracy of the proposed hypothesis is evidenced by a fairly precise coincidence of the average size of chopped particles with the calculated cutting length. The mass ejection range up to 8 meters also shows the effectiveness of the rectangular deflector and the reliability of the conducted theoretical studies.

Here, the rationality of the chosen speed regime of the chopping rotor and the rectangular deflector scheme is demonstrated by the analysis of the ejected mass. Departing feed particles at the end of the bogie side begin to decrease, indicating that a lower mass velocity from the deflector is not advisable.

Here, it is important that the quality of the chopped wet mass meets the zootechnical requirements for silage harvesting and preparation of green mass intended for direct feeding of livestock.

The disadvantage of this study is that the velocity of the airflow created by the grinding rotor is not taken into account when moving the mass through the deflector pipe. However, the machine design includes blades that provide mass ejection through the deflector. In this case, the airflow velocity is approximately 3.0 times less than the linear speed of the knife and blade. Therefore, at the initial stage, theoretical studies were conducted without considering the airflow velocity. Further development of the studies can be carried out taking into account the airflow velocity. However, during the mowing and grinding process, the amount of air entering the grinding chamber is sharply reduced and the airflow velocity in the deflector pipe decreases. Therefore, at this stage of theoretical studies, this process factor is not taken into account.

7. Conclusions

1. To improve the quality of chopped stem fodder, an orienter is included in the harvester's design, ensuring that the mass enters the chopping rotor chamber along the length of the stems. For small farms, a design and technological scheme of the harvester equipped with a rectangular deflector and stem length orienter was developed. Design documentation was developed and a prototype model of the harvester was manufactured.

2. An analytical expression was obtained to determine the forage mass velocity at the deflector outlet. The obtained dependence shows that the change in the forage mass velocity depends on its initial velocity, mass and midship cross-sectional area of the forage, air density, and deflector inclination angle, i.e. all factors affecting the reduction in forage mass velocity are taken into account.

3. As a result of theoretical studies, an analytical expression was obtained to determine the flight range of the forage mass after its exit from the deflector. This dependence makes it possible to determine the rational range of mass ejection from the deflector, considering the loading of forage mass on different areas of the vehicle body.

4. To verify the efficiency of the developed design and technological scheme of the harvester and the reliability of theoretical studies, laboratory research tests of the harvester were conducted during mowing and chopping of alfalfa.

At a PTO rotation speed of 850 min^{-1} (average tractor operation mode), the processes of mowing and chopping rotors, rectangular deflector, and orienter were conducted in a rational mode without disruption of technological processes. The harvester's productivity when mowing alfalfa was 6.22 t/h, the mass ejection range in the horizontal direction was within 7.5...8.0 m (theoretical value – 7.8 m), the average size of chopped particles was 32.89 mm (calculated length – 33.5 mm), i.e. the difference between theoretical and actual values is 1.5 %.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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Data availability

Data will be made available on reasonable request.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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