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DEVELOPMENT OF A LAYER LEVELING TECHNOLOGY THAT REDUCES THE ENERGY INTENSITY OF THE PROCESSES OF MIXING AND DRYING THE FODDER MASS

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The object of the study is to determine the required power leveling device grinder-mixer-dryer. When operating equipment that combines grinding, mixing and drying in one device, there are such problems as energy intensity, the lack of calculation formulas for the theoretical determination of the required power, which makes it difficult to plan the energy intensity of the equipment. As a result of the research, a constructive-technological scheme of the grinder-mixer-dryer equipped with a leveling device was developed. The leveling device, rotating in opposite directions, moves the raised fodder mass to the end walls of the bunker. The operation of the screed tines eliminates excessive forage lift and speeds up the mixing process by moving the forage evenly across the entire width of the bin. The acceleration of the drying process of wet food is explained by the fact that new portions of wet food are constantly exposed to hot air. As a result of theoretical studies an analytical expression was obtained to determine the required power for the process of leveling the layer of forage mass and the required power for the process of leveling the layer of forage mass N_T=0.286 kW was determined. The results of the experimental determination of the required power for the process of leveling the forage mass layer showed the following value N_E=0.273 kW, i.e. the difference between theoretical and actual value is only 4.76 %. This proves the reliability of the obtained analytical expression, which provides the definition of the main parameter of the grinder-mixer-dryer, i.e. required power leveling device. The proposed device and the resulting analytical expression can also be used in feed mixers

Keywords: grinder-mixer-dryer, leveling device, required power, forage mass, layer to be removed

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1. Introduction

Feeding animals, birds and animals with feed flour of animal origin implies the enrichment of the feed mixture with vitamins and mineral supplements. At the same time, global demand for livestock feed will almost double by 2050 due to population growth and an increase in demand for livestock products [1].

In the preparation of fodder meal of animal origin, the main processes are grinding, mixing and drying of fodder [2]. At the same time, grinding helps to obtain fodder meal of the required fraction, useful for consumption by animals and birds. Drying helps to preserve feed for a long time, and also disinfects waste feed raw materials. Mixing helps to eliminate the process of pre-sorting of raw materials and ensures a uniform distribution of various components in feed and feed mixtures. Each of the listed technological processes is important in the preparation of feed, without which it will be impossible to obtain the required quality of highly nutritious feed and feed mixtures. The traditional scheme for the preparation of bone feed meal includes the following stages: raw material grinding, steam or hot water treatment, separation, and drying [3]. At the same time, a little-studied process is the mixing of various components of animal origin, including various bone waste among themselves and with other raw materials, which is also important for the quality of feed.

In general, feeds of animal origin are characterized by increased nutritional and feed value, they are a valuable source of proteins and minerals in the feed rations of farm animals [4]. Animal ingredients can be used as the sole source of dietary protein or in additional combinations with vegetable protein sources [5] for feeding farm animals. For example, in the Republic of Kazakhstan, 91 % of the cattle and 96 % of the sheep are kept in households and small farms with 50...100 head of cattle and 500 head of sheep. Many do not provide themselves with the necessary livestock products, so there is a need to create small dairy and fattening farms and provide them with high-quality feed using efficient technological equipment.

In addition, in the Republic of Kazakhstan, existing small farms containing 50...100 heads of cattle account for about 70 % of the total number of farms. Therefore, the development of the necessary technical means for such farms is a solution to the urgent problem of agriculture.

2. Literature review and problem statement

The paper [6] presents the results of a study of a digester model with temperature, pressure and stirrer speed controllers to study the effect of changes in heat treatment conditions on the quality of fodder meal from poultry by-products. A temperature of 140 °C, a cooking time of 45 minutes and a stirrer speed of 20 rpm have been shown to optimize the feed preparation process. But there were unresolved issues related to the calculation of the required power of the mixer. The reason for this may be the objective difficulties associated with determining the design parameters of the digester. The disadvantage of using this equipment should be noted that in some cases additional grinding of fodder meal particles is required. A way to overcome these difficulties can be to study different designs of mixing screws, the main difference between which is the pitch length. This approach was used in [7], where for screw structures, the calculated simulation results include the speed of feeding particles by the screw, the speed of particles in the screw, etc. However, during the operation of such screws, the energy intensity of the mixing process is very high. All this suggests that it is advisable to conduct a study to reduce energy intensity. This requires a theoretical justification and calculations for the required power of the working bodies for mixing. In addition, the screw turns require some design perfection.

The paper [8] presents the results of a study of preliminary grinding of wet feed. It is shown how the preliminary grinding of wet feed raw materials takes place. However, no information is provided on the removal of moisture and fine final grinding of feed particles. Also, the work does not pay attention to determining the required power of the working bodies. Co-mixing observed during grinding is not taken into account.

The paper [9] presents the results of a study on the processing of chicken feathers. It is shown that chicken feathers were ground in a meat grinder, mixed in a vertical mixer. The dried powdered material was then mixed with the rest of the experimental diet ingredients and granulated into 2 mm pellets before feeding to the fish. But there were unresolved issues related to the determination of equipment parameters, which is necessary for a feasibility study. The reason for this may be objective difficulties associated with the lack of available theoretical and experimental methods for determining the required power of the devices used. In addition, the processing of chicken feathers is carried out in various devices, which makes it difficult to determine the power of each device separately.

The paper [10] presents the results of a study of the extrusion method in the processing of keratin-containing waste using an extruder that implements the principle of thermal vacuum exposure to raw materials. It is shown that in the process of preparation for extrusion, the raw material is dried to a moisture content of 28 % and cleaned of mechanical impurities. In the second stage, the raw material is fed into the extruder and pushed into the barrel under the pressure of the screw press. In the extruder, the temperature gradually rises, taking into account the increase in pressure. The pen changes from a solid state to a melting one. At this stage, the feather turns into a crumbly product. At the third stage, the pen is ground into flour and packaged. But there were still unresolved issues related to pre-drying and mixing. The reason for this is the limited possibilities associated with the design and technological scheme of the extruder. A way to overcome these difficulties can be the use of additional devices. However, this requires certain costs. In addition, information is not provided on determining the required power of the extruder, which is necessary to determine the energy intensity of the equipment. All this suggests that it is advisable to conduct research on feed processing using the improvement of mechanical and thermal processes [11]. For example, in the production of rabbit bone meal, operations such as high-pressure cooking, protease hydrolysis, colloid milling, vacuum freeze drying, sieving, and ball milling have been performed. At the same time, the influence of various cooking conditions, the influence of cooking temperature on the speed of sifting rabbit bone meal was emphasized. It was found that the influence of the rotation speed on the dispersion index of a particle is greater than the influence of time [12]. However, it should be noted that no studies have been conducted on the mixing of various feed components, since the mixing process requires separate process equipment. All this suggests that it is advisable to conduct a study on equipment that combines the technological processes for the preparation of feed. The way to overcome these difficulties can be the combination of such energy-intensive processes as drying and fine grinding in one unit [13]. Drying occurs when high shear forces are applied to the product. As a result, the process of grinding particles occurs. To study the influence of the temperature regime of processing on the degree of grinding, studies are also given on mixing the paste without temperature treatment and in the process of drying with stirring. According to the research results, it was determined that when the drying process is carried out in a horizontal paddle mixer while the product is mixed in a wet state, the product undergoes grinding, and the main grinding of the product to fine particles occurs in the first 30...40 minutes of the process, while the product is in a wet, non-rigid state. Subsequently, the average fraction size remains practically constant, however, particle agglomeration is prevented. At the same time, the degree of grinding is influenced by the presence of heat treatment, since the change in the average particle size occurs more intensively. Regarding the combination of processes, it should be noted that the combination of grinding by cutting with the supply of the crushed material to the cutting pairs due to inertia forces can significantly reduce the specific energy consumption [14]. However, there are unresolved issues related to the derivation of analytical expressions for determining the required power, which affects the energy intensity of the equipment.

As is known, the combination of drying processes with grinding in one apparatus intensifies the drying process [15]. However, there are unresolved issues related to the mixing process in the drying and grinding equipment, which limits the production of homogeneous feed in the case of processing a variety of raw materials of animal origin. The reason for this is the lack of special working bodies that contribute to energy-intensive mixing during drying. All this suggests that it is advisable to conduct a study to substantiate the design and technological scheme of a device that combines the processes of grinding, mixing and drying, as well as determining the required power of working bodies that help reduce the energy intensity of mixing and drying processes of various wet feed raw materials of animal origin in one device.

Thus, it is most efficient to carry out grinding, mixing and drying of feed particles of animal origin in one device. As a result of the analysis and review of scientific and technical information, it is especially important to note the lack of justification for the design and technological scheme and parameters of the grinder-mixer-dryer of feed, as well as the lack of analytical expressions for determining the required power aimed at reducing the energy intensity of mixing and drying processes, which is an unresolved problem of technological processes of feed preparation.

3. The aim and objectives of the study

The aim of the study is development of design and technological solutions that at reducing the energy intensity of mixing and drying processes.

To achieve this aim, the following s are accomplished:

– to substantiate the constructive-technological scheme of the grinder-mixer-dryer of fodder;

– theoretically determine the required power for the process of leveling the forage mass layer;

– experimentally determine the required power for the process of leveling the forage mass layer.

4. Materials and methods of research

When preparing feeds, it is necessary to grind the particles to the required size, dry them for their subsequent preservation, and mix various feed raw materials to increase their uniformity, which generally affects the quality of the prepared feeds. To carry out these technological processes, the necessary technological equipment is required for grinding, mixing and drying the fodder mass with a decrease in the energy intensity of the processes of mixing, drying and their acceleration. Therefore, the object of research is to determine the required power of the grinder-mixer-dryer, equipped with a leveling device. At the same time, a hypothesis was proposed, which consists in the use of a leveling device in the form of a finger shaft, which ensures the elimination of an excessively high rise in the forage mass and accelerates the mixing process, as well as reduces the energy intensity of the process and accelerates the drying process of wet fodder due to the fact that new portions of wet food.

When developing a constructive-technological scheme of the grinder-mixer-dryer, methods of analysis of agricultural machines were applied. When developing design documentation, the Compass-3D program was used. Typical calculations were carried out using the built-in tools in the Compass 3D application library program.

For a theoretical study, the methods of theoretical mechanics and the formulation of the equation of motion of a body of variable mass are applied. Using the equation of motion of the body by the moved mass, an analytical expression is obtained to determine the required power for the process of leveling the layer. In the process of mixing, mass is added, i. e. instantaneous interaction of two masses. From this it is clear that in this case the resultant force during the movement of a body with a variable mass is determined by the equation of Meshchersky [16]. Analytical expressions are obtained for determining the resistance forces and mass movement when the mass layer is torn off by a finger shaft. Taking into account that separation of the layer of mass by the fingers of the leveling shaft occurs at the end of the fingers, therefore the speed of the layer movement will be determined as the linear speed of the leveling shaft at the ends of the fingers.

When conducting experimental studies, the method of conducting single-factor experimental studies was applied. Experimental studies were carried out in a designed grinder-mixer-dryer. The supply of hot air for drying occurred convectively from a thermal heater. Grinding and mixing was carried out by means of an auger, on the turns of which knives are located. The auger was made of a seamless pipe with a diameter of 102 mm, coils (feathers) with a diameter of 300 mm, knives, trunnions. The auger is fastened to the housing by means of pins and two flanges with a diameter of 95*140 into the walls of the housing with bolts, washers and nuts. To rotate the auger, two 62132RS sealed bearings (dimensions 65*120*23 mm), a chain drive and a 3 kW helical gear motor are used. For chain transmission selected driving and driven sprockets: sprocket with a pitch of 19 on the pin of the screw, the number of teeth Z=44, inner diameter d=55 mm, pitch 19; sprocket with a pitch of 19 on the motor-reducer shaft, number of teeth Z=18, inner diameter d=30 mm, pitch 19. The screw speed was varied in the range of 5–50 rpm by means of a Leg frequency converter. In the upper part of the structure, a leveling device with fingers is provided, which is fixed with the help of two flanges 160*28, bolts, washers, nuts, and rotates by means of two closed bearings GOST 107 (dimensions 35×62×14 mm) and a worm gear motor with a power of 1.5 kW, 50 rpm/min Automation of the grinder-mixer-dryer is carried out through external push-button posts installed in the control cabinet. Inside the drying chamber, two thermocouples are installed at two different points above the screw to measure the temperature.

Wet egg shell waste with chicken yolk waste 10–30 mm in size was loaded into the grinder-mixer-dryer. To measure the temperature, an InfiRAY C210 thermal imager with a resolution of 256×192 pixels was used. To determine the moisture in raw materials and feed flour, a universal moisture meter with an external probe AMF038, manufactured by AMTAST (USA), was used. Characteristics: humidity measurement range: from 2 to 70 %; measurement step 0.5 %; error ±1 % f.s.; measurement time – less than 1 sec.; operating temperature from –10 to 60 °C; power supply – battery 1.5 V, type AAA, 2 pcs. An AS 220/R2 electronic balance was used to measure the weight. To determine the moisture content of the dried mass, after a certain time, the unloading damper of the grinder-mixer-dryer was slightly opened and a certain portion of the mass was filled into a plastic bag to determine the moisture content of the mass. An oven was used to reliably determine the moisture content of the obtained sample.

Determination of the required power for the process of leveling the forage layer was carried out using the Fluke 345 instrument. The instrument is a combination of a power analyzer, a power quality recorder and a current clamp. Voltage (phase voltage) 234 V, measurement amperage 0.19 A. The presence of current clamps based on the Hall effect made it possible to measure direct current using a power meter without an open circuit.

5. The results of research on the substantiation of the structural and technological scheme and parameters of the grinder-mixer-dryer

5. 1. Substantiation of the structural and technological scheme of the grinder-mixer-dryer

Currently, modern feed mixers are used as a chopper-mixer. In the designs of these machines, two horizontal augers with knives are installed at the bottom of the bunker. Each auger has right and left turns. During operation, the right and left helical blades (turns) of the auger direct the feed mass to the center, then it rises up and collapses to the end wall of the bunker. In this case, two-circuit mixing occurs. However, during the operation of such a distributor-mixer, the energy intensity of the mixing process is very high.

To eliminate this disadvantage, two screws can be installed in the upper part of the bunker, however, this complicates the design of the machine and increases its cost, i.e. this reduces the demand for the machine from farms. To reduce the energy intensity of the mixing process, let's provide for the installation of a finger roll, i. e. a leveling device, in the upper part of the horizontal auger. The leveling device, rotating in opposite directions, moves the raised fodder mass to the end walls of the bunker. At the same time, the manufacture of a leveling device in the form of a finger shaft is much simpler than the manufacture of a screw conveyor. It is known from the constructive-technological scheme that the operation of the finger shaft ensures the elimination of an excessively high rise in the forage mass and the acceleration of the mixing process. In addition, a uniform movement of the forage mass across the entire width of the bunker is carried out. All this provides a significant reduction in the energy intensity of the process, and such a leveling device is used for the first time in the designs of the grinder-mixer-dryer of fodder.

Such a leveling device in this design of the machine provides a reduction in the energy intensity of the process and an acceleration of the drying process of wet feed. This is due to the fact that new portions of wet food are constantly exposed to hot air.

Thus, the developed constructive-technological scheme has versatility and provides a reduction in the energy intensity of the mixing process and acceleration of the fodder drying process (Fig. 1). Therefore, such a constructive-technological scheme of the grinder-mixer-dryer of feed is proposed, consisting of a hopper 1, a horizontal auger 2, a leveling device in the form of a finger shaft 3 and a pipe for supplying hot air 4.

Horizontal auger in accordance with Fig. 2 has a seamless pipe 1, coils 2, knives 3 installed at the ends of the coils. At the other end, the auger has a coil that directs the mass from the end wall to the middle of the hopper. It can be seen from the diagram that the mass being moved by the turns of the auger, the fingers of the leveling device is directed in the opposite direction. At the same time, the excessive rise of the mass is eliminated and a new portion of the wet mass gets under the hot air all the time, thereby accelerating the process of drying and mixing the feed.

Knives installed at the end of the turns crush the mass and eliminate clogging of feed. Thus, the developed constructive-technological scheme of the grinder-mixer-dryer ensures the implementation of the processes of grinding, mixing and drying feed.

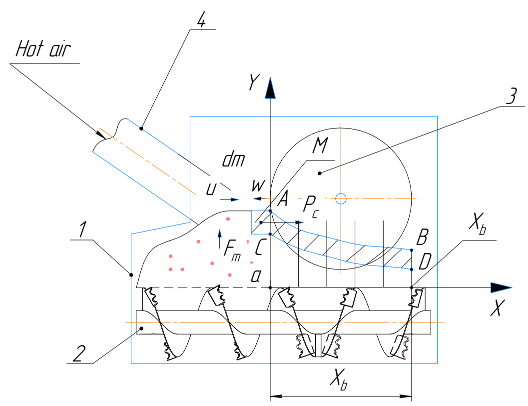

Fig. 1. Structural and technological scheme of the grinder-mixer-dryer of feed, equipped with a leveling device

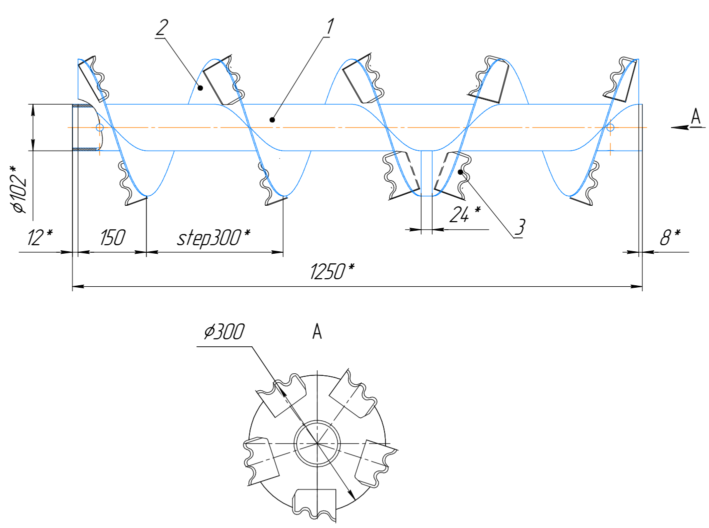

Fig. 2. Scheme of a horizontal auger

5. 2. Theoretical determination of the required power for the process of leveling the forage layer

In the design of the developed grinder-mixer-dryer, a leveling device is used for the first time, therefore, the theoretical determination of the required power in the leveling process is a solution to an actual theoretical problem.

During operation, the turns of the feed chopper-mixer-dryer screw move the mass, and it is directed to the center, i.e. it is possible to assume that the feed mixture with mass dm moves to the center of the bin with speed u. In this case, the mass movement speed dm can be considered equal to the mass movement speed created by the screw working body.

For example, with a two-row arrangement of fingers, every half-turn of the shaft, a row of fingers rakes a certain layer from the surface of the feed mixture and directs it to the end walls of the hopper at a speed, and at the same time, a row of fingers experiences the resistance force P_C (Fig. 1).

The raked mass M meets the mass dm and the mass is added, i.e. instantaneous interaction of two masses.

In this case, the resultant force during the movement of a body with a variable mass is determined by the equation of Meshchersky [16]:

$$F_P = P_C + \frac{dm}{dt}(u+v). \tag{1}$$

To solve this equation, each component of this equation is determined separately.

The value of the mass m moved by the screw is determined by the formula:

$$m = \left(\pi R_k^2 - \pi R_b^2\right) S \rho_k, \tag{2}$$

where R_k, R_b – radii of the chamber and the screw drum, m; S – screw pitch, m; p_k – feed mixture density, kg/m^2.

This mass moves along the screw and rises up. In this case, the second supply of the lifted mass is determined by the formula:

$$q = \frac{\left(\pi R_k^2 - \pi R_b^2\right) S \rho_k}{t_{sc}}, \tag{3}$$

where t_{sc} – time spent on one revolution of the screw, s.

The time for one revolution of the auger must be expressed in terms of the angular frequency of the leveling device (shaft) w.

The screw rotation time is determined by the formula $t_{sc} = \frac{2\pi}{\omega_{sc}}$, and the time for half a revolution of the shaft $t_b = \frac{\pi}{\omega_b}$, from here $2\Pi = w_{sc} t_{sc}$, $\Pi = w_b t_b$, that's why $w_{sc} t_{sc} = 2 w_b t_b$, from here:

$$t_{sc} = \frac{2\omega_b t_b}{\omega_{sc}}. \tag{4}$$

Taking into account formula (4), let's determine the productivity of the screw:

$$q = \frac{\left(\pi R_k^2 - \pi R_b^2\right) S \rho_k \omega_{sc}}{2\omega_b t_b}. \tag{5}$$

Considering that:

$$t_b = \frac{\pi}{\omega_b},$$

then in the formula (5) t_b is shrinking.

Here the resulting formula, multiplying by t_b, determine the value of the mass m, which falls in front of a row of fingers of the comparing device (shaft):

$$m_b = \frac{\left(R_k^2 - R_b^2\right) S \rho_k \omega_{sc}}{2} \cdot t_b. \tag{6}$$

To determine the derivative of the mass m_b by time t_b let's differentiate formula (6) and obtain:

$$\frac{dm_b}{dt_b} = \frac{\left(R_k^2 - R_b^2\right) S \rho_k \omega_{sc}}{2}. \tag{7}$$

Considering the speed of mass movement dm equal to the speed of movement of the mass by the screw working body $U = \frac{S\omega_{sc}}{2\pi}$, and the speed of movement of the mass by the leveling device (finger shaft) is determined by the formula:

$$\upsilon = \frac{\pi n_b}{30} R_{bc},$$

where n_b – frequency of rotation of the leveling device in the form of a finger shaft, min^{-1}; R_{bc} – radius of fingers to the center of gravity of the moved mass, m.

In this case, the resistance force acting on a number of fingers of the leveling device with the speed of the moved mass dm, is determined by the formula:

$$F_m = \frac{dm_b}{dt_b}(U + \upsilon) = \frac{1}{2}\left(R_k^2 - R_b^2\right) S \rho_k \omega_{sc} \left(\frac{S\omega_{sc}}{2\pi} + \omega_b R_{bsc}\right). \tag{8}$$

Now it is necessary to determine the value of the resistance force P_C. The value of this force depends on the thickness of the removed layer, on the mass lifted by the screw working body.

If to know the equation of the curve AB and CD, then it is possible to calculate the cross section of the layer to be removed by the limited curves AB and CD.

In this case, it can be assumed for the curve AB $y_1 = a_0 - a_1 x - a_2 x^2$, and the BC curve can be described by the equation $y_2 = b_0 - b_1 x - b_2 x^2$.

If the coefficients of these equations are known, then the calculation of the area ABCD is provided by means of a double integral [17, 18]:

$$\begin{aligned} S_p &= \iint_{ox_b AB} \mathrm{d}x\,\mathrm{d}y - \iint_{ox_b CD} \mathrm{d}x\,\mathrm{d}y = \\ &= \int_0^{x_b} \mathrm{d}x \int_0^{a_0 - a_1 x - a_2 x^2} \mathrm{d}y - \int_0^{x_b} \mathrm{d}x \int_0^{b_0 - b_1 x - b_2 x^2} \mathrm{d}y = \\ &= \int_0^{x_b} y \Big|_0^{a_0 - a_1 x - a_2 x^2} \mathrm{d}x - \int_0^{x_b} y \Big|_0^{b_0 - b_1 x - b_2 x^2} \mathrm{d}x = \\ &= \int_0^{x_b} \left(a_0 - a_1 x - a_2 x^2\right)\mathrm{d}x - \int_0^{x_b} \left(b_0 - b_1 x - b_2 x^2\right)\mathrm{d}x = \\ &= \left(a_0 x - \frac{a_1 x^2}{2} - \frac{a_2 x^3}{3}\right)\Bigg|_0^{x_b} - \left(b_0 x - \frac{b_1 x^2}{2} - \frac{b_2 x^3}{3}\right)\Bigg|_0^{x_b} = \\ &= \left(a_0 x_b - \frac{a_1 x_b^2}{2} - \frac{a_2 x_b^3}{3}\right) - \left(b_0 x_b - \frac{b_1 x_b^2}{2} - \frac{b_2 x_b^3}{3}\right). \end{aligned} \tag{9}$$

Thus, the cross-sectional area of the layer to be removed is determined by one row of fingers of the leveling device.

In this case, the mass of the layer to be removed is determined by the formula:

$$M_c = S_p \cdot B_b \rho_k, \qquad (10)$$

where B_b – bunker width, m.

The actual value of the force of separation of the layer by a leveling device in the form of a finger shaft must be determined experimentally.

In theoretical terms, the value of the mass separation force M_C from the feed mixture layer can be represented as follows:

$$P_c = M_c q f_c, \qquad (11)$$

where f_c – coefficient of separation of the feed mixture layer from the feed monolith.

Thus, analytical expressions were obtained to determine the resistance forces and mass movement dm when the mass layer is torn off by a leveling device in the form of a finger shaft. Taking into account that the separation of the layer of mass by the fingers of the screed shaft occurs at the end of the fingers, therefore, the speed of movement of the layer v_c will be determined as the linear speed of the screed at the ends of the fingers and it is determined by the formula:

$$v_c = \frac{\pi n_b}{30} R_n, \qquad (12)$$

where R_n – radius of the leveling shaft at the ends of the fingers, m.

The analysis of Fig. 1 also shows that the value of the length x_b can be taken as the diameter of the leveling device (finger shaft). After determining all the resistance forces acting on the fingers of the screed, it is possible to determine the required thickness of the screed with the fingers.

$$N_{po} = F_p \cdot v_c = \left(F_m + P_c\right) v_c =$$
$$= \left[\begin{array}{l} \frac{1}{2}\left(R_k^2 - R_b^2\right) S \rho_k \omega_{sc} \cdot \left(\frac{S\omega_{sc}}{2\pi} + \omega_b R_{bc} \right) + \\ + \left(\begin{array}{l} \left(a_0 x_b - \frac{a_1 x_b^2}{2} - \frac{a_2 x_b^2}{3} \right) - \\ - \left(b_0 x_b - \frac{b_1 x_b^2}{2} - \frac{b_2 x_b^2}{3} \right) \end{array} \right) \cdot B_b \rho_k q f_c \end{array} \right] \times$$
$$\times \frac{\pi n_b}{30} R_n. \qquad (13)$$

Using the equation of motion of the body by the moved mass, an analytical expression is obtained to determine the required power for the process of leveling the layer. For the practical application of the formula (13) it is necessary to have the equation of curves AB, CD and the value of the coefficient of separation of the layer from the feed monolith. Therefore, after conducting experimental studies, the reliability of theoretical studies is checked.

The actual value of the required power for the mixing process with a screed will be determined from the results of experimental studies, and the reliability of the theoretical studies carried out will also be verified.

5. 3. Experimental determination of the required power for the process of leveling the forage mass layer

To determine the reliability of theoretical studies, a grinder-mixer-feed dryer (Fig. 3) was developed and designed according to the design and technological scheme shown in Fig. 1.

In the developed grinder-mixer-dryer, the finger shaft in the form of a leveling device is installed above the screw perpendicular to each other. In the main working area, the following processes are carried out: knife grinding, screw-turn mixing, finger leveling and convective drying with hot air (Fig. 4).

a *b*

Fig. 3. General view of the experimental grinder-mixer-dryer feed: *a* – front view; *b* – side view

a *b*

Fig. 4. General view of the working area of the grinder-mixer-dryer at idle: *a* – right side view; *b* – left view

Experimental studies were carried out on the developed grinder-mixer-dryer to justify the technological processes of layer leveling, mixing and drying of feed materials (Fig. 5).

To determine the power, the current intensity was measured by phases at idle and with loaded feed raw materials by connecting the FLUKE 345 device to the auger gear motor and leveling device (finger shaft) (Fig. 6).

a *b*

Fig. 5. Working area of the grinder-mixer-dryer with raw materials: *a* – right side view; *b* – left view

a *b*

Fig. 6. Current measurement: *a* – at the auger gear motor; *b* – at the gear motor leveling device

The results of the research showed (Fig. 7) that the fingers of the ejecting shaft (leveling device) removed from the upper layer of the lifted mass a layer of thickness 0.1 m. Processing of the experimental data showed that the upper layer is described by the empirical equation: $Y=0.35-0.2x-0.1x^2$ those curve AB is described by this equation. Accordingly, the lower layer is also described by the equation: $Y=0.25-0.2x-0.1x^2$ Hence it is known that the coefficients of the equation have such values: $a_0=0.35$; $b_0=0.25$; $a_1=b_1=0.2$; $a_2=b_2=0.1$.

Now let's present practical calculations based on the theoretical analytical expressions obtained to determine the theoretical value of the required power for the process of leveling the layer during the operation of the grinder-mixer-dryer. For the calculation, let's use the following parameters of the developed grinder-mixer-dryer:

$R_k=0.175$ m; $R_b=0.05$m; $S=0.3$ m; $r_k=800$ kg/m^3;

$w_{sc}=3.14$ rad/s; $w_b=4.71$ rad/s; $R_{bc}=0.25$m; $R_n=0.3$ m;

$B=0.5$ m; $x_b=0.6$ m.

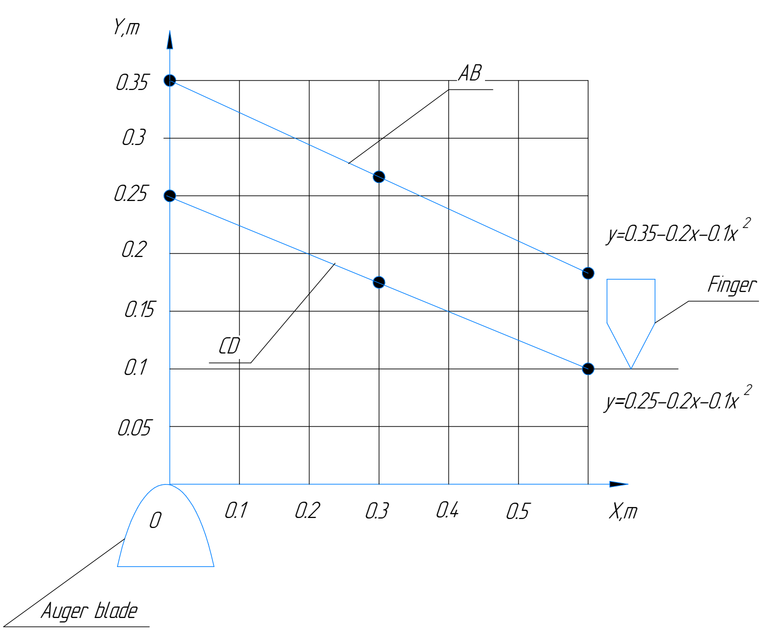

Fig. 7. The results of the studies

Theoretical calculations according to the obtained analytical expression (13) show that the required power expended on the process of leveling the forage mass layer is $N_T=0.286$ kW.

Now let's find the required power in the process of leveling the layer during the operation of the chopper-mixer-dryer experimentally. As a result of experimental studies, the required power was determined by the formula:

$$N = IU\cos\phi 3, \qquad (14)$$

where I – current strength, A; U – phase voltage, 234 V; $\cos\varphi=0.81$; 3 – number of phases.

To determine the current strength, the insignificant work of the cooler and the electronics installed in the control cabinet was neglected. The experiments were carried out on mixed fodder wet raw materials (eggshell, egg yolk waste) with simultaneous loading of raw materials. To test theoretical studies, this process of operation of the leveling device was chosen due to the fact that in the process of leveling and simultaneous drying of the layer, an excessively high rise in the fodder mass is eliminated and the mixing process is intensified, and the process of drying newly incoming portions of wet fodder particles under convectively supplied hot air is also accelerated.

In this case, the supply of feed raw materials was carried out by loading raw materials through the top cover of the hopper, while the top leveling shaft was stopped. After loading, all closing covers, raw material bins were closed. The rotation of the auger was carried out in the range of 10–50 rpm, the rotation of the leveling device with the set rotational speed was 50 minutes^{-1}. Hot air was supplied with a temperature of 130 °C inside the working area, which was automatically regulated using thermocouples, thermal relays and automation. If necessary, it was possible to turn on the hammer crusher with a rotation speed of 1500 min^{-1} to include dry ingredients in the feed mixture. Table 1 shows the results of varying the speed of the screw at idle (without raw materials).

Table 2 shows the results of the work of each device separately, which is part of the grinder-mixer-dryer, as well as the results of work in pairs and as a whole together. In Table 2, in the following sequence, the results of the work are obtained: leveling device; fan; fan+one heat electric heater (9 kW); fan+two heat electric heaters (18 kW); hammer crusher; fan+leveling device+auger; fan+one heat electric heater+leveling device+auger with $n=50$ min^{-1}; fan+two electric heaters+leveling device+auger with $n=50$ min^{-1}; auger with $n=50$ min^{-1}; auger with $n=50$ min^{-1}+leveling device.

Table 1

The results of varying the speed of the screw to determine the average current strength at idle

Screw speed n, rpm	Current I, A	Current frequency v, Hz	Phase voltage U, V
10	2.90	10.8	234
20	2.32	20.5	234
30	2.16	30.0	234
40	2.05	40.0	234
50	2.00	50.0	234

Let's use the results of the last two measurements to find the difference in current strength using formula (15). First, for this, let's find the average values from Table 2, i. e. $I_{a.sc.}$=6.14 A and $I_{a.sc.+l.d.}$=5.56 A:

$$I = I_{sc} - I_{sc+l.d.}. \tag{15}$$

Thus, let's obtain the current strength I=0.58 A.

It is known that for the idling of the leveling shaft, the expended current strength is equal to 0.1 A, and then on the layer leveling workflow I=0.48 A.

Substituting the last numerical value into formula (14) obtain the required power 272.91=273 W or 0.273 W.

Table 2

The results of the operation of the grinder-mixer-dryer devices for determining the current strength

Type of worker devices	Current strength I by phases, A			Current frequency v, Hz	Phase voltage U, V
	I_1, A	I_2, A	I_3, A		
leveling device	0.1	0.1	0.1	50	234
Fan	0.9	–	–	50	234
Fan+one heat electric heater (9 kW)	13.3	13.2	13.9	50	234
Fan+two heat electric heaters (18 kW)	27	26.35	27	50	234
Hammer crusher	0.17	0.35	0.22	50	234
Fan+screeder+auger with n=50 min^{-1}	2.9	2.9	3.36	50	234
Fan+one heat electric heater+leveling device+auger with n=50 min^{-1}	14.8	14.40	15.1	50	234
Fan+two electric heaters+leveling device+auger with n=50 min^{-1}	28.45	27.40	28.40	50	234
Auger with n=50 min^{-1}	6.14	6.13	6.15	50	234
Auger with n=50 min^{-1}+leveling device	5.56	5.55	5.57	50	234

The results of the experimental work, measurements and calculations show that the required power of the leveling device was the following value N_E=0.273 kW. From the above, it is known that the required power of the leveling device according to the obtained analytical expressions was equal to N_T=0.286 kW. This shows that the difference between the theoretical and actual values of the required power of the screed is only 4.76 %. This proves the reliability of the obtained analytical expression. It can be used to determine the required power of screeders designed to intensify the mixing and drying of feed.

6. Discussion of the results of a study to determine the required power of a grinder-mixer-dryer equipped with a leveling device

As a result of the research, Fig. 1 shows a constructive-technological scheme of the chopper-mixer-fodder dryer, equipped with a leveling device. In existing feed mixers, the mixing process is carried out by horizontal augers with left and right turns. In this case, the food collects in the center and rises up until it collapses. This method of mixing process is used in all existing feed mixers [19]. However, with this mixing method, the energy intensity of the process is very high. To reduce the energy intensity of the mixing process, it is possible to install one auger in the upper part of the hopper above the horizontal auger, which has right and left turns in the upper part of the hopper. But during the operation of the auger, the movement of the feed mass towards the end walls of the bunker is carried out along one wall of the bunker, and a "Dead zone" appears along the other side wall of the bunker, which significantly reduces the homogeneity of the feed mixture [20]. To eliminate this disadvantage, two screws can be installed in the upper part of the bunker, however, this complicates the design of the machine and increases its cost, i.e. this reduces the demand for the machine from farms.

For uniform leveling of the fodder mass, we have proposed a simple finger shaft. A patent for the invention was obtained for the design of this device [21]. This leveling device removes the top layer of the rising mass and directs it to the end wall of the hopper. This reduces the energy intensity of the mixing process, and it should be noted that a new portion of feed gets under the hot air all the time, i.e. there is an intensification of the process of drying feed. In addition, the use of such a leveling device in existing chopper-dryers, feed mixer-dryers and choppers has not been found. Thus, the use of such a leveling device in a grinder-mixer-dryer is the technical novelty of this article and the main feature of the existing method of mixing and drying feed. It should also be noted the effectiveness of the installed knives on the turns of the auger, which allows, together with the mixing process, to grind the feed mass.

As a result of theoretical studies an analytical expression was obtained to determine the required power for the process of leveling the forage layer when it is lifted by an auger working body (13). It should be noted here that the mixing process in existing mixers with high feed lift under its own weight collapses to the end walls. In the developed device, the feed is moved by the auger in one direction, and the layer moved by the leveling device is directed against the mass being moved by the auger working body. From this it can be seen that the addition of two masses occurs, i.e. the mixing process is carried out in a completely new way. Therefore, for a theoretical consideration of the process, we proposed the application of the theory of motion of a point of variable mass. We did not find the application of this theory to describe the mixing process with simultaneous drying and grinding in existing works. This can also be seen from the fact that in existing mixers the mixing process takes place by completely different methods. Thus, as a result of theoretical studies, a new method of mixing and drying in a grinder-mixer-dryer was described and an analytical expression was obtained to determine the required power for the layer leveling process. The composition of the analytical expression includes all the design and kinematic parameters of the developed grinder-mixer-dryer, equipped with a new leveling device. Therefore, the resulting expression has become a mathematical model of the process of leveling and discarding the forage mass layer.

According to the results of experimental studies, it can be seen that after 90 minutes the moisture content of the feed mass decreased from 60 % to 7 % due to the operation of the grinder-mixer-dryer (Fig. 3). The efficiency of the drying plant is confirmed by the fact that when the leveling device rotates at a speed of 50 min^{-1} and with a two-row arrangement of its fingers for every 0.6 s. a new portion of wet fodder mass gets under the jet of hot air (Fig. 5). For example, when the unit is operating without a finger shaft, the process will proceed as follows: when the auger is working, the feed mass first rises to a certain height and after that the collapse of the mass begins. At the same time, the time between each collapse of the forage mass is longer than 0.6 s. However, to date, we have not conducted such comparative studies. For the development of this study, it is planned to conduct such a comparative experimental study.

Analysis of Table 2 shows that the last two rows of the table show the results of measuring the current intensity by phases, i.e. when the auger is operating without a leveling device (I_1=6.14 A) and when the auger is operating with a leveling device. (I_1=5.56 A). At the same time, the inclusion of the leveling device provided a power reduction of 0.33 kW. This proves the operability of the leveling device, which reduces the power for mixing and drying the fodder mass by 9.45 %.

As a result of experimental studies, it was found that the obtained analytical expression adequately describes the process of leveling the forage mass layer. It can be seen here that the difference between the calculated and actual values of the required power is only 4.76 %, i.e. less than 5.0 %.

This minimum decrease is explained by the fact that the developed device was small-sized. Thus, the results of experimental studies prove that the use of a leveling device reduces the energy intensity of the mixing process and accelerates the drying process of feed.

The main advantage of the conducted studies is the use of a leveling device, which reduces the energy intensity of the process, and it is confirmed by comparative experimental studies. In addition, this leveling device can be included in the design of existing distributors - feed mixers. Another important advantage is the mathematical description of the layer leveling process using the theory of motion of a variable mass point. The reliability of the obtained analytical expression is proved by experimental studies. Mathematical description of the process of leveling the forage mass layer was not found in other literary sources.

The proposed device (Fig. 1, position 3) and the resulting analytical expression (13) can be used in existing feed mixers, various devices that combine the processes of grinding, mixing and drying in one apparatus. To expand the scope of this device and the analytical expression, it is necessary to install a screeder in large machines and check the validity of the resulting expression when using existing feed mixers with a screeder.

The development of this leveling device is associated with its use in existing feed preparation machines, in the development of the processes of grinding, mixing and drying feed in one device. The use of the developed leveling device in the designs of grinders-mixers-dryers, existing feed mixers is not difficult. Based on the foregoing, it should be noted the importance of developing a methodology for determining the required power of the leveling device as part of the structural and technological scheme of the feed chopper-mixer-dryer based on a reasonably obtained analytical expression with experimental confirmation, which is of great scientific and practical importance.

A certain disadvantage should also be noted here, which consists in the fact that when designing a leveling device having other dimensions, it is required to experimentally obtain an empirical equation that describes the level of the upper layer to be collapsed. This is a certain limitation of the applicability of the proposed analytical expression in determining the required power of devices of other sizes. At the same time, obtaining a system of equations for other used chopper-mixer-dryer designs is a continuation and development of the proposed method for determining the required power for the process of leveling the forage mass layer.

7. Conclusions

1. The structural-technological scheme of the grinder-mixer-dryer of feed, consisting of a hopper, a horizontal screw, a leveling device in the form of a finger shaft and a branch pipe for supplying hot air, is substantiated. To reduce the energy consumption of the mixing and drying process, for the first time in the chopper-mixer-dryer designs, a leveling device was installed in the upper part of the horizontal auger. At the same time, excessive mass lifting is eliminated and a new portion of wet mass is constantly exposed to hot air to intensify the drying and mixing of feed. Knives installed at the end of the turns crush the mass and eliminate clogging of feed. The developed constructive-technological scheme of the chopper-mixer-dryer ensures stable performance of the processes of grinding, mixing and drying feed.

2. An analytical expression has been obtained to determine the required power for the process of leveling the forage mass layer. The composition of the analytical expression includes all the design and kinematic parameters of the developed grinder-mixer-dryer, equipped with a new leveling device. Therefore, the resulting expression has become a mathematical model of the process of leveling and discarding the forage mass layer.

3. To verify the reliability of theoretical studies, experiments were carried out on an experimental feed grinder-mixer-dryer. The results of the experimental determination of the required power for the process of leveling the layer of forage mass showed the following value N_E=0.273 kW, and the theoretical value of the required power – N_T=0.286 kW, i. e. the difference between the theoretical and actual screed value is only 4.76 %. This proves the reliability of the obtained analytical expression, which provides the definition of the main parameter of the grinder-mixer-dryer, i. e. required power leveling device.

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

Manuscript has no associated data.

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