*The object of the study is to determine the critical impact speed during shell destruction, study crack formation in the shell, and grind the shell. When operating a grinder-mixer-dryer, problems arise such as determining the speed of impact on the shell depending on the height of its fall, the lack of ability to determine the speed of shell fall from certain heights, which complicates planning the operation of the finger shaft. As a result of research, it was found that an auger with knives crushes and moves feed raw materials, and the impact-spreading shaft ensures partial grinding of fragile raw materials and intensive processes of mixing and drying wet feed with uniform filling of the installation hopper. The appearance of cracks on the shell when it falls from a height of 0.15 m has been experimentally recorded. Therefore, this speed of impact of the shell on a metal surface is the critical peripheral speed of the impact-spreading shaft, which ensures partial crushing of the shell. As a result of theoretical studies, an analytical expression was obtained that provides the determination of the shell impact speed depending on the height of its fall. The value of the critical peripheral speed of the fingers of the impact-spreading shaft is determined to be 1.66 m/s. The experimental results showed the effective occurrence of grinding, mixing and drying processes. Moreover, within 15 minutes of operation of the installation, the wet shell was crushed in accordance with the requirements. The uniformity reached up to 90 % within 4 to 6 minutes of its operation, and drying proceeded at a rate of 26.54 % per hour. All this proves the effectiveness of the processes of grinding, mixing and drying wet food, and also confirms the reliability of theoretical research*

*Keywords: grinder-mixer-dryer, impact-spreading finger shaft, cracks, destructive speed, eggshell*

# JUSTIFICATION OF PARAMETERS OF IMPACT-SPREADING FINGER SHAFT FOR GRINDER-MIXER-DRYER USING THE EXAMPLE OF EGGSHELLS

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## 1. Introduction

Currently, animal feed is widely used in feeding farm animals, birds and animals. When preparing such feeds, various technological processes are used, such as grinding, drying and mixing various feed components. In addition, these feeds are perishable due to their high moisture content. In many cases, it is advisable to carry out various technological processes in parallel. For example, when preparing food from eggshells, it is necessary to dry, grind and mix them with various other feed components. Processing eggshells in the form of secondary raw materials for food enterprises is a resource-saving technology [1] that facilitates the preparation of necessary feed. At the same time, improving equipment for grinding eggshells is important. Many scientists are conducting research to improve equipment for grinding eggshells, including using a ball mill [2] and a crusher [3]. The most acceptable is the use of working bodies with high technical and economic characteristics in equipment for grinding eggshells [4], aimed at processing – crushing and grinding raw material particles to the required granulometric size. Therefore, it is relevant to develop and substantiate working bodies that facilitate the implementation of the crushing and grinding process in an effective device. In this aspect, the most promising direction of research is the development of working bodies aimed at combining several technological processes and techniques in one device. Therefore, the development and justification of the parameters of an installation that ensures parallel processes of drying, grinding and mixing is a solution to an urgent problem in agriculture.

## 2. Literature review and problem statement

As is known, the precursor to the separation of crushed raw materials into parts is often the formation of initial cracks

in the crushed raw materials that arise during impact and destructive loading, thereby contributing to the formation of non-uniform surfaces and damage in the crushed pieces and particles. According to the catastrophe theory [5], one of the factors of crack formation is the length of the crack. The critical crack length is influenced by the opening of the crack tip [6], or more precisely by the radius of the crack tip. Energy must be expended to increase the length of the crack. The potential energy of a body can either increase or decrease. If it increases, then this indicates that energy is supplied from outside to grow the crack by increasing the external load. At the same time, the occurrence and growth of a crack can be achieved by a certain influence and in the form of force. Often, the formation of cracks can occur during an impact, which can be described by the contact theory of impact by G. Hertz, the wave and classical theories of impact. For example, during an elastic impact, you should pay attention to the coefficient of recovery, which can be characterized by rebounds. Moreover, the stronger the rebound, the more the recovery coefficient increases [7], which is proportional to the strain rate directed towards destruction. It is worth noting that as the height of the egg drop increases, the deformation rate also intensifies, which is reflected in an increase in cracking. At the same time, dropping an egg from a higher height contributes to the formation of not only cracks on the shell, but also cracks and broken parts, which again proves the influence of the height of the drop and the force of the impact on the rate of deformation and destruction. The destruction of materials by impact, as a type of deformation of materials, was studied by the famous scientist Jung. As a result of the compressive load, the material breaks. When atoms approach each other, a gap occurs. The shear direction and displacement (dislocations) are of no small importance.

It was found in [8] that hot-cold exposure can lead to the formation of more cracks and a wider distribution of cracks than cold exposure, which leads to more serious damage to the ground samples. Thus, hot and cold impact has a better effect on destroying the crushed sample than cold impact alone. All this suggests that it is advisable to conduct a study devoted to grinding with parallel heating or drying.

The time of impact of the working body on a particle of the crushed material is important [9]. But the issues related to determining the impact velocity on particles of crushed material, especially those dropped from a low altitude, are still unresolved. The reasons for this may be objective difficulties associated with measuring the falling velocity of particles during grinding. An option to overcome the corresponding difficulties may be to theoretically determine the impact speed of crushed particles depending on the height of the fall. All this allows us to state that it is advisable to conduct a study devoted to obtaining an analytical expression that will help determine theoretically the speed of falling of crushed particles from different heights. The most effective destruction of basic solid materials occurs under impact loading [10]. But still little attention is paid to determining the value of the critical peripheral speed of a rotating shaft with impact elements. All this significantly affects the effectiveness of the impact, which promotes crack formation in the crushed particles. When considering cracking, one should also pay attention to quantum theory, which requires the adoption of rules of reasoning, called quantum reasoning, which is based on standard logic [11]. In this case, you should pay attention to the validity of the parameters of the installation with which the supplied raw materials are crushed.

In [12], a hammer design with sharp-toothed edges is used, which instantly acts on the crushed element with a force from the cheek of the tooth, creating a crack plane and pushing the separated halves of the crushed element apart in directions perpendicular to the fracture plane. However, insufficient attention is paid to the direction of impact and the issue of particle dispersion is not considered at all. In [13], it is proposed to strike with the central part of the hammer, which reduces the wear of the hinge holes during the operation of the hammer. However, the influence of the peripheral speed of the impact elements is not specified, which does not entirely justify the efficiency of grinding. The work [14] notes that when grinding wet grain, there is insufficient performance of the working parts associated with the use of the impact method in crushing. A possible solution to this problem can be achieved by combining the cutting and impact method.

At the same time, the work [15] describes the design of a knife-type hammer, which allows grinding wet feed raw materials. However, the rationale for the effectiveness of combining grinding techniques is not fully presented. Also, no research has been conducted on eliminating excess moisture from grain during the process of simultaneous drying and grinding, which could increase the level of efficiency of the proposed method. In [16], it was found that the pressure of the air flow field increased from the center of the rotor to the end of the crusher hammer. However, information on the rate of discharge of crushed raw materials into the crusher is not fully disclosed, which affects the peripheral speed of the crusher rotor. The work [17] reports that the initial grinding occurs more intensively than subsequent grinding. However, no effective methods have been proposed for intensifying subsequent grinding based on parallel grinding with other technological processes (for example, drying), which would effectively affect the formation of new surfaces in the crushed particles, which are also blown with hot air. In [18], based on the discrete element method, the rotor of an impact crusher with a vertical shaft was modeled. The effects of different guide plate angles on the acceleration characteristics of the rotor were studied by extracting particle velocity data. For the rotor to operate, the speed of all particles must be taken into account. The higher the particle population speed, the greater their total kinetic energy and the better the particle fragmentation effect. However, no attention has been paid to the study of crack formation in crushed particles, which could optimize the operating mode of the crusher rotor. It is noted in [19] that the particle size decreased with increasing grinding speed. However, the studies did not pay attention to the speed and height of discharge of crushed particles, which could also intensify the grinding process. It should be taken into account that in a hammer crusher, when the rotor rotates, the hammers simultaneously swing around their axes. This rocking affects the movement of the rotor, causing vibration [20]. At the same time, the vibration is also influenced by the height of the discharge of the crushed raw materials into the grinding working area. Therefore, finding the height and velocity of the release is essential. The work [21] describes the preliminary and final grinding of waste feed raw materials with a focus on fine grinding of low-fat raw materials, which increases the efficiency of complex processing of raw materials. However, the work does not theoretically substantiate the parameters of technical devices, which reduces the scientific significance of the research. The work [22] analyzes the design of technological equipment that combines the processes of grinding, drying and mixing, which has a number

of technical and economic growth indicators. The disaggregation process has an important function aimed at intensifying heat and mass transfer in colloidal capillary-porous materials. However, the work does not provide theoretical justifications and calculations for optimizing grinding and determining operating parameters. [23] notes how the appropriate contour of the impact segments of the ring armor has a significant impact on the grinding efficiency. In this work, the invention is based on providing a design for the impact segment of ring armor with a high crushing effect. However, no justifications are given for the parameters of the installation used.

A promising direction of development is the development of equipment that combines the simultaneous implementation of a number of technological processes in one device. For example, the development of a grinder-mixer-granulator ensures the effective preparation of bulk and granulated feed [24]. For the necessary preparation of complete feed mixtures, feed mixer dispensers equipped with a vertical auger are used [25]. Currently, grinder-mixer-feed dispensers equipped with horizontal augers with knives are widely used [26]. At the same time, the widespread use of natural sorbents, such as bentonite clays, sapropel, zeolites, phosphites, characterized by a diverse mineral composition [27], as well as non-food waste from poultry farms and meat processing plants, is promising as non-traditional feed additives. The use of such feed and other raw materials often requires drying. For example, there is a tray dryer for grass seeds. It contains a drying tray and consists of an air distribution duct system, an air heater and a fan with an electric motor [28]. Here, the distribution of the thermal agent over the surface of the tray is carried out by a mobile air distribution system. A drum dryer has found practical application, providing drying of high-moisture grass with infrared irradiation [29]. As a result of experimental studies, it was found that at an air temperature of 70 °C, grass humidity from 70 % reached 30 % in 2 hours [30].

Thus, the results of a review of literature sources show that there is a tendency to develop more universal technical means that promote the intensification of drying and mixing processes through simultaneous grinding. It should be noted that the mixing process in existing feed mixers is carried out by lifting the mass until it collapses. At the same time, the energy intensity of the mixing process is very high. Reducing energy intensity can be achieved by paralleling the processes of mixing, drying and grinding in one device, where the working parts are important. Particular importance should be given to the justification of the design and technological scheme of the grinder-mixer-dryer, theoretical studies to determine the impact speed of the working parts and laboratory tests of the grinder-mixer-dryer. Based on this, the development of universal technical means that ensure the efficient completion of the processes of grinding, mixing and drying feed raw materials is a solution to the pressing problem of procurement and preparation of feed.

## 3. The aim and objectives of the study

The aim of the study is to substantiate the parameters of the grinder-mixer-dryer, ensuring a reduction in the energy intensity of the processes of grinding, mixing and drying, as well as accelerated processes.

To achieve this aim, the following objectives are accomplished:

– to substantiate the design and technological scheme of the grinder-mixer-dryer;

– to determine the theoretically critical impact velocity during the destruction of the eggshell;

– to determine the reliability of theoretical studies and laboratory results of the grinder-mixer-dryer.

## 4. Materials and methods of research

When developing the design and technological scheme of the laboratory installation, methods for designing agricultural machines were used, taking into account the parallel flow of the processes of grinding, mixing and drying wet feed raw materials, and methods of intensifying various processes occurring in parallel were also taken into account. In this case, important attention should be paid to the justification of the parameters of the impact-spreading finger shaft for the chopper-mixer-dryer of feed raw materials, which essentially affect the mechanism of destruction and spreading of solid feed raw materials and, ultimately, contribute to the intensification and increase in productivity of crushing and grinding as well as drying and mixing feed raw materials. Therefore, the object of the study is to determine the critical impact speed during the destruction of feed raw materials eggshells, study crack formation in eggshells, crushing and grinding eggshells in a grinder-mixer-dryer. At the same time, a hypothesis has been proposed that consists in the possibility of theoretical determination of the critical impact speed, which contributes to the effective destruction of the shell, taking into account the justification of the design parameters of the impact-spreading finger shaft of the grinder-mixer-dryer.

When determining the rate of destruction of an eggshell as a result of its fall from a certain height, a method was used to solve the main problem of dynamics. The theoretical determination of the critical impact speed during the destruction of an eggshell was carried out by drawing up a dynamics equation. For the reliability of the research, a comparison was made of the theoretical and experimental values of the speed of falling eggshells.

When conducting experimental studies of the process of drying eggshells, the method of single-factor experimental studies was used. Each experiment was carried out in triplicate. As a result of processing the experimental data, the standard deviation was determined. The homogeneity of variance in parallel experiments was accepted according to the Cochran criterion.

The sieve analysis method was used to analyze samples. In the experimental studies, modern instruments were used – an AKE-824 power quality analyzer, MW-300T electronic scales, sieves, measuring instruments – tape measure, calipers, micrometer and laboratory installation (grinder-mixer-dryer). Hot air for drying was supplied convectively from an electric heater with a power of 18 kW. To heat the air, two heating elements are installed in the electric heater. The power of each heating element was 9.0 kW. In this case, the capacity of the working area of the bunker was 0.2 m³. Grinding and mixing were carried out by means of a screw, on the turns of which knives are located, as well as by means of an impact-spreading finger shaft. The auger was rotated by a 3.0 kW gearmotor, and the impact-spreading finger shaft was rotated by a 1.5 kW gearmotor. During the operation of the installation, the air temperature was automatically heated to 130 °C. The automation of the grinder-mixer-dryer was carried out through external push-button stations installed in the control cabinet. Samples of the feed mixture were taken at certain intervals

to determine the quality of grinding, moisture and uniformity. To measure temperature, an InfiRAY C210 thermal imager with a resolution of 256×192 pixels was used. To determine the moisture in raw materials and feed mixture, a universal moisture meter with an external probe AMF038, manufactured by AMTAST (USA), was used.

## 5. Results of research to substantiate the design and technological scheme and parameters of the spreading mechanism of the grinder-mixer-dryer

### 5. 1. Justification of the design and technological scheme of the grinder-mixer-dryer

Currently, there are well-known designs of a grinder-mixer-dispenser. In the design of this machine, at the bottom of the bunker there are two augers with knives. These screws have right and left turns. When working, they mix the feed into the center of the bunker, while the feed rises up until it collapses and the process of mixing feed occurs. However, this process is carried out with high energy intensity. Therefore, we have proposed that in order to reduce the energy intensity of lifting the mass, it is necessary to scatter or transport the mass to the end walls of the hopper. In this case, you can use a screw with right and left turns, which ensures the movement of mass to the end walls of the hopper. However, the auger transports the mass along one wall. Therefore, it is necessary to install two augers in the upper part of the hopper, but this grinder-mixer has a complex design and high cost.

To spread the mass to the end walls of the hopper, we have proposed an impact-spreading finger shaft. In addition, when preparing feed of animal origin, in many cases the feed raw material has a high moisture content (for example, eggshells with yolk residues). Therefore, in this case, in addition to grinding and mixing, there is a need to use a drying process. Based on the task, we have developed a design and technological diagram of a grinder-mixer-dryer (Fig. 1).

The main difference between this installation and existing feed mixers is the presence of a spreading shaft with impact fingers. When changing the structure, the fingers of this mechanism provide an impact action and create sufficient crushing of the material. During operation, the auger directs the feed in one direction, and the fingers scatter in the opposite direction and ensure that a fresh portion of the material gets under the hot air, which speeds up the processes of drying and grinding the feed. In addition, the fingers of the impact-spreading shaft limit the lifting of the mass, which also reduces the power required for the mixing process.

In this case, for this installation, it is important to determine the critical peripheral speed of the fingers, i.e. determine the optimal rotation speed of the pin shaft. On the one hand, the linear speed of the fingers should not be less than the speed of the mass moved by the auger, and on the other hand, the intensity of mixing the feed material should be sufficient.

If the feed material is eggshell, then the linear speed of the fingers should be equal to the speed of destruction of the eggshell. In addition, this speed should ensure intensive flow movement of the scattered feed material.

This installation is intended for processing feed of animal origin, including feed from meat and bone raw materials of various animals and eggshells. When working with eggshells, the linear speed of the fingers of the spreading mechanism must be equal to the critical speed of destruction of the eggshell by a free blow. To determine the critical rate of destruction of an eggshell by a free blow, special experiments were carried out. Moreover, each experiment was carried out in triplicate.

At the same time, the nature of the destruction of eggshells when falling from different heights was determined. In this case, the first appearance of cracks occurred when dropped from a height of 0.15 m. Therefore, the nature of the appearance of cracks when an eggshell fell from a height of 0.15; 0.3 and 0.6 m was studied.

To assess the nature of the destruction of the eggshell, after it fell from a certain height, the presence of cracks of a certain length was determined. At the same time, depending on the number of cracks having a certain length, the probability of the occurrence of this event was determined. After such processing of the experimental data, the nature of the destruction of an eggshell when it falls from various heights is shown in Fig. 2.

From Fig. 2 it can be seen that when an eggshell weighing 4 g falls from different heights, the average length of cracks was 3...5 mm. It was also found that the value of the critical speed of destruction of the eggshell was equal to the speed of the fall of the eggshell from a height of 0.15 m.

The values of the speed of falling eggshells from a height of 0.3 m were determined – $v_k=2.3$ m/s and from a height of 0.6 m – $v_k=3.158$ m/s.
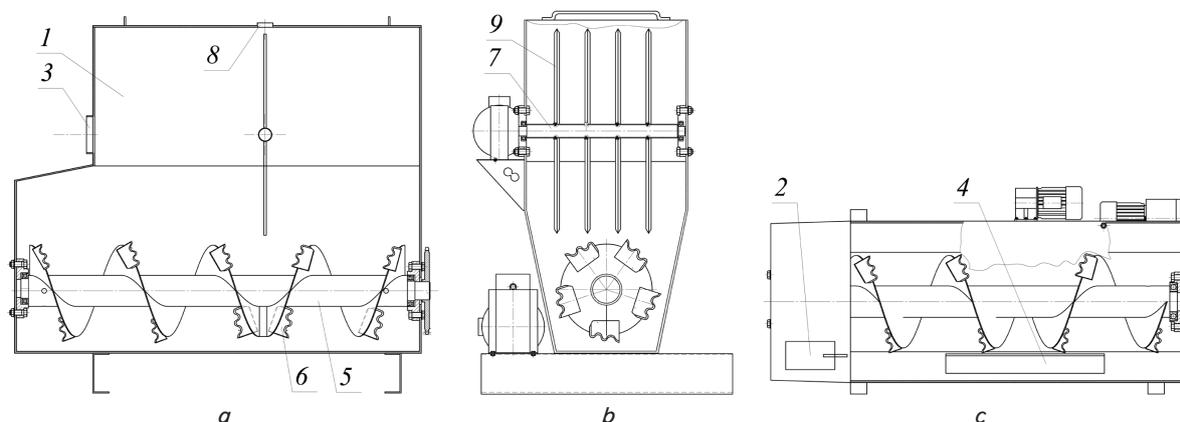


Fig. 1. Design and technological diagram of the grinder-mixer-dryer: $a$ — front view; $b$ — side view; $c$ — view from above; 1 — body; 2 — pipe for feeding feed; 3 — pipe for supplying hot air; 4 — unloading hatch; 5 — horizontally positioned rotating spiral screw; 6 — knives; 7 — shock-spreading finger shaft; 8 — outlet air duct; 9 — spreading fingers
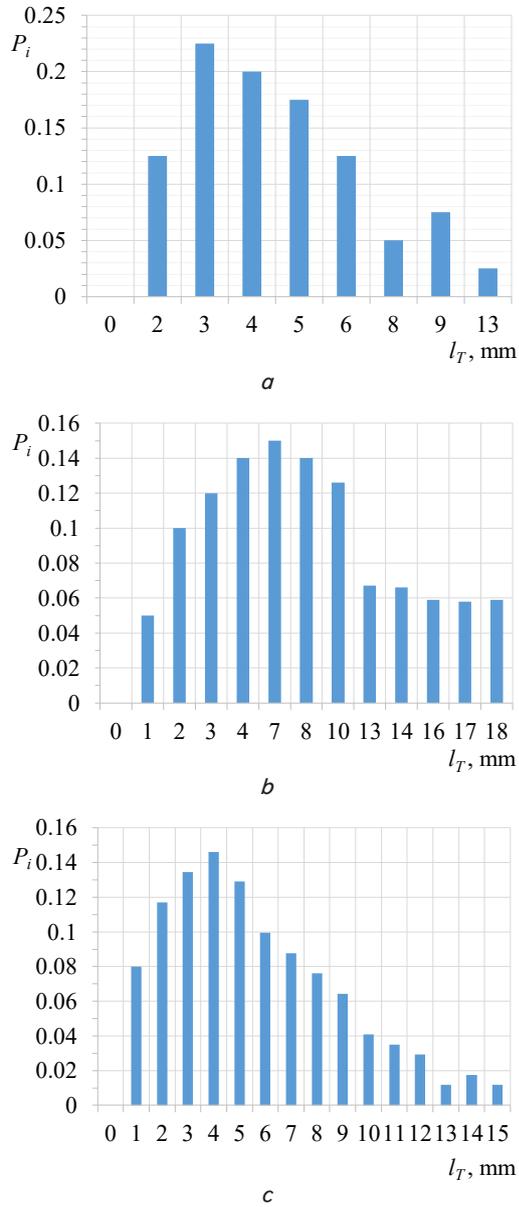
Fig. 2. Probability of crack distribution depending on its length when an eggshell falls from different heights: $a$ — when an eggshell falls from a height of 0.15 m; $b$ — when an eggshell falls from a height of 0.3 m; $c$ — when an eggshell falls from a height of 0.6 m

However, we were unable to accurately determine the speed at which eggshells fall from a height of 0.15 m. Therefore, there is a need to theoretically determine this critical destructive speed. Determining this speed makes it possible to determine the rational rotation speed of the impact-spreading finger working body. It must also be efficient for moving other feed materials.

At the same time, the theoretical determination of this critical rate of destruction of eggshells is important for various theoretical foundations related to the development of agricultural machines.

**5. 2. Theoretical determination of the critical impact speed when breaking an eggshell**

To do this, it is necessary to determine the value of the speed of movement of the eggshell depending on the height of its fall.

To solve this problem, we compose a dynamics equation [31]:

$$mv\frac{dv}{dh}=P-\frac{C_x\rho S}{2}v^2, \qquad (1)$$

where $m$ – eggshell mass, kg; $v$ – eggshell movement speed, m/s; $h$ – height of eggshell fall, m; $P$ – gravity of eggshell, N; $C_x$ – body drag coefficient; $\rho$ – air density, kg/m$^3$; $S$ – cross-sectional area of the body, m$^2$.

Expressing mass in terms of gravity and thrust, we obtain:

$$\frac{2P}{g}v\frac{dv}{dh}=2P-C_x\rho Sv^2,$$

$$\frac{2P}{C_x\rho S}\cdot\frac{v}{g}\cdot\frac{dv}{dh}=\frac{2P}{C_x\rho S}-v^2. \qquad (2)$$

We introduce the notation $\frac{2P}{C_x\rho S}=a^2$.

It should be noted here that $a^2$ has the dimension m$^2$/s$^2$. The equation then looks like this:

$$\frac{a^2}{g}\cdot\frac{vdv}{dh}=a^2-v^2. \qquad (3)$$

Dividing we get:

$$\frac{vdv}{a^2-v^2}=\frac{g}{a^2}dh. \qquad (4)$$

To determine the speed of movement of the eggshell, it is necessary to integrate equation (4).

In this case, the initial speed of the eggshell $v=0$ and the final speed of movement of the eggshell after it falls from a height $h$, that is $v=v_k$. The path of movement of the shell at the beginning is $h=h_k$, and at the end $h=0$:

$$\int_0^{v_k}\frac{vdv}{a^2-v^2}=\frac{g}{a^2}\int_{h_k}^0 dh. \qquad (5)$$

When multiplying both sides of the equation by 2, the value of the right side of the equation is equal to the derivative of the denominator, then the integral is equal to the natural logarithm of the denominator:

$$\int_0^{v^2}\lg(a^2-v^2)dv=\int_h^0\frac{2g}{a^2}(h)dh,$$

$$\lg(a^2-v_k^2)-\lg a^2=-\frac{2gh_k}{a^2},$$

$$\frac{a^2-v_k^2}{a^2}=e^{-\frac{2gh_k}{a^2}}. \qquad (6)$$

Equation (6) without the logarithm is written as follows:

$$-v_k^2=a^2e^{\frac{2gh_k}{a^2}}-a^2,$$

$$v_k^2=a^2-\frac{a^2}{e^{\frac{2gh_k}{a^2}}},$$

$$v_k=a\sqrt{1-\frac{1}{e^{\frac{2gh_k}{a^2}}}}. \qquad (7)$$

First, we determine the theoretical value of the critical destruction speed of the eggshell, i.e. speed of an eggshell falling from a height of 0.15 m.

In this case, as noted above, we take the mass of the eggshell $m=0.004$ kg. In this case, with such a mass, the eggshell was destroyed and had a round-angled shape with a length of 50 mm and a width of 45 mm, so the cross-sectional area was $S=0.00225$ m$^2$ and $C_x=1.11$, $\rho=1.29$ kg/m$^3$ [32], $a=4.9355$, $e^{2gh_k/a^2}=1.128$.

Now we can determine the actual value of $a^2$.

To determine the reliability of the obtained value of the critical speed of destruction of an eggshell, it is necessary to determine the theoretical value of the speed when an eggshell falls from a height of 0.3 and 0.6 m. The obtained theoretical speed values are compared with the experimental values of the speed of falling of the eggshell.

To plot a graph of the speed of falling eggshells depending on the height of its fall, its theoretical values were calculated. The results of the calculation using formula (7) and the experimental values of the speed of falling eggshells from a height of 0.3 and 0.6 m are given in Table 1.

Table 1

The value of the speed of falling of an eggshell depending on the height of its fall

| No. | Eggshell falling speed, m/s | Eggshell drop height, m | | | | |
|---|---|---|---|---|---|---|
| | | 0.15 | 0.3 | 0.4 | 0.5 | 0.6 |
| 1 | Theoretical speed, m/s | 1.66 | 2.26 | 2.59 | 2.84 | 3.055 |
| 2 | Experimental speed, m/s | – | 2.3 | – | – | 3.158 |

From Table 1 it can be seen that a comparison of theoretical and experimental values of the speed of falling eggshells from a height of 0.3 and 0.6 m showed good convergence of the two positions. In this case, the error was in the range of 1.74...3.26 %.

Therefore, we take the theoretical value of speed $\upsilon_k=1.66$ m/s as the critical speed of an eggshell impact.

At this speed, we determine the rotation frequency of the impact-spreading finger shaft (at $G_p=0.3$ m) according to formula (8) and obtain a value equal to 52.86 min$^{-1}$:

$$n=\frac{30\upsilon_k}{\pi G_p}. \qquad (8)$$

In addition, to determine the nature of the study of the speed of falling eggshells, the obtained calculation results are presented in the form of a graphical dependence of the speed of movement of the eggshell on the height of its fall (Fig. 3).

The graph also shows that as the height of the eggshell fall increases, the intensity of the fall speed decreases. This decrease is typical for all falling solid materials, which also proves the reliability of the obtained analytical expressions.

Moreover, this rate of destruction was determined for brittle materials. In addition, this installation can be used for preliminary grinding of meat and bone raw materials of birds and fish with different moisture content.

During the work, it was found that the main grinding should be carried out with knife working bodies installed at the end of the auger turns. In addition, the finger working element moves a certain layer of feed. In this case, eggshells and other fragile feed materials must be crushed at a lower speed than the critical destructive impact speed of the eggshell.
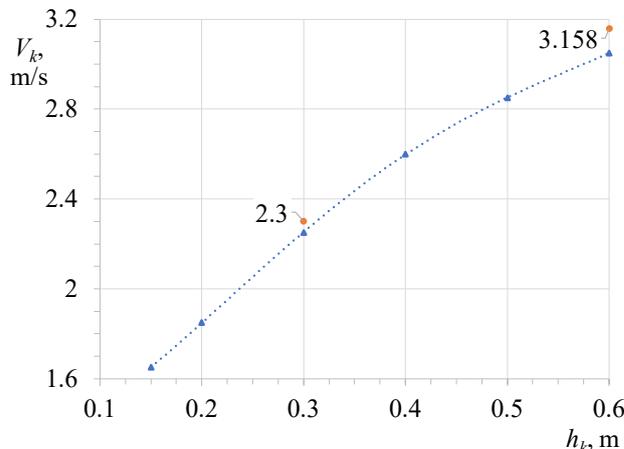


Fig. 3. Eggshell speed values depending on the height of its fall

In previous studies, a finger spreading drum was used to separate the leafy parts of grasses from pre-chopped hay [33]. In this case, the rotation frequency of the drum was determined on the condition that the particles of stem feed, due to centrifugal forces, slipped off the fingers until the beginning of the third quarter of the rotation circle of the finger drum. In this case, the frequency of the finger drum was determined by the formula:

$$n\geq\sqrt{\frac{900\cdot g\cdot f}{\pi^2 r_b}}, \qquad (9)$$

where $f$ – coefficient of friction of feed material on the impact surface.

To determine the rotation frequency of the finger drum, using this formula it is necessary to determine the value of the friction coefficient of an eggshell with a humidity of 60 %. In this case, the movement of the wet mass began at an angle of inclination of the steel surface of 38°, that is $f=0.78$.

The rotation frequency of the finger drum, which was determined by formula (9), was equal to 48.25 min$^{-1}$. This rotation frequency turned out to be almost the same as the rotation frequency of the finger spreading drum, which was determined taking into account the critical rate of destruction of the eggshell.

Thus, with the radius of the fingers $r_p=0.3$ m, the rotation speed of the impact-spreading finger shaft was in the range of 48.25...52.86 min$^{-1}$.

As a result of the research, the linear speed of the throwing fingers was determined with the condition that it ensures the destruction of fragile feed raw materials and the continuous movement of feed materials without scattering or capturing the feed on the second revolution of the impact-spreading finger shaft.

Therefore, it was planned to conduct experimental studies with a finger radius $r_p=0.3$ m and a shaft rotation speed $n_p=50$ min$^{-1}$. In this case, the peripheral speed at the ends of the fingers is 1.57 m/s.

### 5. 3. Results of experimental studies of the processes of grinding, mixing and drying eggshells

According to the developed design and technological scheme, drawing documentation was developed and a laboratory installation was manufactured (Fig. 4).
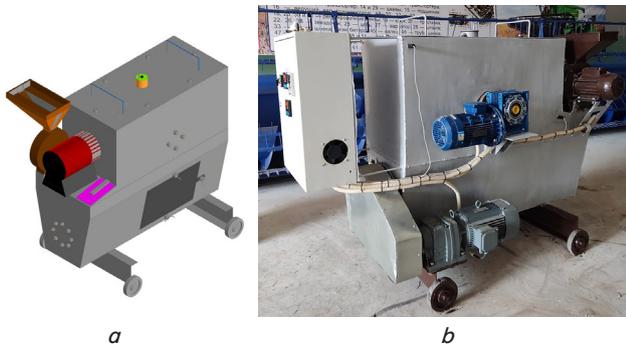
Fig. 4. General view of the laboratory installation (grinder-mixer-dryer): *a* — 3D model of a grinder-mixer-dryer; *b* — photo of the grinder-mixer-dryer

An auger with a diameter of 300 mm was installed at the bottom of the bunker, and knives from a serial feed mixer-dispenser were installed at the end of the auger blades. In the upper part of the structure, there is an impact-spreading finger shaft, secured with two flanges. The design provides for a supply of drying agent from an electric heater. The main installation parameters are given in Table 2.

Table 2

Technical characteristics of the grinder-mixer-dryer

| Technical specifications | Parameter values |
|---|---|
| Rotation speed of the auger with knives, r/m | up to 50 |
| Screw diameter, mm | 300 |
| Screw shaft diameter, mm | 102 |
| Rotation speed of the impact-spreading finger shaft, r/m | 50 |
| Diameter of the shaft with fingers, mm | 600 |
| Auger drive power, kW | 3 |
| Finger shaft drive power, kW | 1.5 |
| Number of knives, pcs | 20 |
| Number of sharp edges on the knife, pcs | 3 |
| Dimensions of the working area, mm | 1,300*500*1,050 |
| Electric heating temperature, °C | up to 130 |

In the beginning, experiments were carried out to determine the pattern of changes in the processes of grinding and drying feed raw materials. For this purpose, the operating modes of the auger, impact-spreading finger shaft and electric heater, as well as an automatic mode for regulating the hot air temperature, were launched. At the same time, eggshells with the remains of the yolk with a moisture content of 39.5 % were loaded into the installation bunker.

During experiments to evaluate the process of grinding feed raw materials, samples were obtained to determine the quality of feed grinding. The quality of grinding feed raw materials for feeding roosters and hens is expressed by the diameter of the crushed feed raw materials, which should be within 1...5 mm. The experimental results are shown in Table 3.

The experimental results show that the quality of grinding meets the requirements within 15 minutes of operation of the installation. At the same time, the quality of crushed raw materials with a diameter of 1...5 mm reaches 90 % in 15 minutes of work and subsequently this amount of crushed particles stabilizes. There is a decrease in the number of crushed particles with a diameter of more than 5 mm and an increase in the number of finely ground particles from 5 % to 10 %. From here we know that for high-quality grinding of eggshells, 15 minutes of operation of the installation is enough. Moreover, after grinding, the feed mass has a uniform structure necessary for feeding birds and other animals (Fig. 5).

During the experiments, samples were taken every 15 minutes of operation of the installation to determine the moisture content of feed raw materials. The initial moisture content of the feed mass was 39.5 %. A graph of changes in humidity depending on the duration of the drying process is shown in Fig. 6.

Analysis of the dependencies showed that at the initial stage of the drying process, a more intense change in humidity is observed, and at the end of the drying process, the change in humidity decreases, and this can be seen from the resulting equation, which has a second-order term:

$$W_i = 39.5 - 0.442T_i + 0.0002T_i^2. \tag{10}$$

Here, also differentiating the resulting equation, we determined the rate of change in humidity for a given feed raw material using the formula:

$$V_W = \frac{dW_i}{dT_i} = \left(39.5 - 0.442T_i + 0.0002T_i^2\right) =$$
$$= -0.442 + 0.0004T_i, \%/h. \tag{11}$$

From the graph (Fig. 6) it can be seen that during the operation of the installation, the rate of change in humidity is 26.54 %/h, and this shows the efficiency of the installation.

Table 3

Quality of crushed feed raw materials depending on the operating time of the installation

| No. | $d_n$, mm | $t$, min | $d_k$, % | | | $T_n$, °C | $n_{sh}$, r/m | $m_g$, kg |
|---|---|---|---|---|---|---|---|---|
| | | | $d_k>5$ mm | $d_k=1–5$ mm | $d_k<1$ mm | | | |
| 1.1 | | 15 | 9 | 91 | – | | | |
| 1.2 | 30 | 20 | 7 | 93 | – | 20 | 50 | 50 |
| 1.3 | | 25 | 5 | 95 | – | | | |
| 2.1 | | 15 | 8 | 90 | 2 | | | |
| 2.2 | 30 | 30 | 4 | 91 | 5 | 130 | 50 | 50 |
| 2.3 | | 45 | – | 91 | 9 | | | |
| 2.4 | | 60 | – | 90 | 10 | | | |

Fig. 5. General view of eggshells before and after grinding:
*a* — photo of eggshells before crushing; *b* — photo of
eggshells after crushing
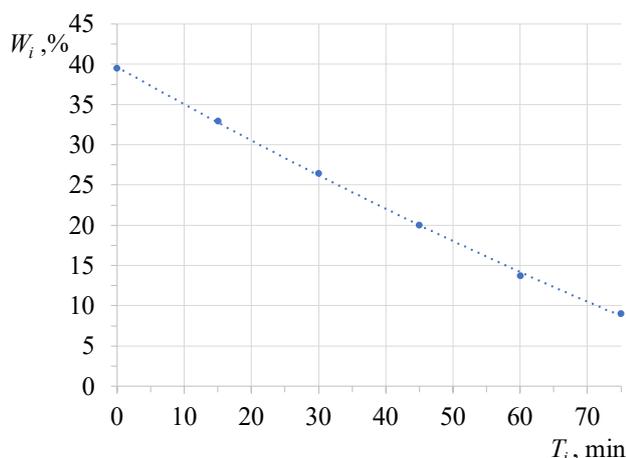


Fig. 6. Graph of changes in the moisture content
of eggshells with yolk waste with a moisture content
of 39.5 % depending on the duration of
the drying process

During the operation of the installation, special experiments were carried out to evaluate the mixing process. After drying the feed raw materials, the hot air flow was turned off and a control component (peas – 3 mm) was introduced, and after the installation was running, samples (10 pieces each) were obtained after 2, 4 and 6 minutes to determine the homogeneity of the mixture. The experimental results are shown in Table 4.

Table 4

Effect of mixing time on the uniformity
of the feed mixture

| Installation operating time, min | 2 | 4 | 6 |
|---|---|---|---|
| Uniformity, % | 80.2 | 89.9 | 91.3 |

These results also show the efficiency of the plant when mixing feed raw materials. It is known that when preparing mixed feed, the homogeneity of the mixture should be within 90...95 %. From Table 4 it can be seen that the mixing time on this installation is only 4...5 minutes, and this proves the high efficiency of the installation when performing the process of mixing feed raw materials.

In these experiments, the required power of the installation was also determined without an impact-spreading pin shaft and with an impact-spreading device. During the operation of the installation, the power consumed for the operation of the auger and the impact spreading device was equal to 3.32 kW, and when the impact spreading finger shaft was turned off, the power consumed with one auger was 3.66 kW. From this, it is clear that the impact-spreading pin shaft provides a reduction in power consumption by 10.24 %. It should be noted here that the value of this reduction depends on the volume of feed loaded. If the plant's workload increases, then the reduction in power consumed by the processes should be significant.

The results of theoretical and experimental studies show that the inclusion of an impact-spreading finger shaft in the design of the installation ensures acceleration of the processes of grinding, mixing and drying of feed.

In fact, it was found here that a reduction in power consumption occurred when the spreading process was turned on. At the same time, this process eliminates excessive lifting of the mass, which contributes to a sharp increase in the torque on the screw shaft. In this case, the impact-spreading finger shaft supplies a certain dosed mass under the hot air. This helps speed up the drying process. In addition, when the device operates without an impact-spreading finger shaft, a large portion of the mass collapses. At the same time, in the composition of the collapsed portion, a significant part of the mass does not fall under the hot air. This collapsed mass is moved in a dense layer by a screw working body. In this dense layer, many particles do not fall under the blade working element, which is installed along the outer surface of the auger blade. When the impact-spreading finger shaft operates, a dosed portion of the mass falls under the auger, i.e. the collapsed mass falls under the auger working body several times in small portions. In this case, the number of masses falling under the auger blade increases significantly, i.e. the intensity of the process of grinding eggshells increases. In addition, when the impact-spreading finger shaft moves the mass and the process of hitting the fingers on the eggshell particles occurs, the eggshell is also crushed. Thus, the inclusion of an impact-spreading finger shaft in the design and technological scheme of the grinder-mixer-dryer ensures acceleration of the processes of grinding, mixing and drying eggshells.

It should also be noted that the theoretical determination of the peripheral speed of the impact-spreading finger shaft increases the intensity of destruction of the eggshell and in the process of its operation there is a continuous movement of the mass. The results of experimental studies showed rapid drying of feed raw materials, as well as a fairly rapid achievement of mixture homogeneity to the required value, that is in 4–5 minutes of installation operation. All this proves the reliability of the theoretically determined peripheral speed of the fingers of the impact-spreading shaft, as well as the inclusion of the impact-spreading finger shaft in the design of the installation, which ensures the intensity of the processes of grinding fragile materials, drying wet feed raw materials and mixing feed components in the preparation of feed mixtures and animal feed.

In the process of conducting research, we studied the starting raw material – eggshells of the following size and weight: length 0.035 m; width 0.035 m; thickness 0.00044 m; weight 0.00086 kg. Special experiments determined the values of the force of destruction of eggshells under static conditions and it amounted to 2.8449 N, and the density of eggshells was 1,595 kg/m$^3$.

## 6. Discussion of research results to substantiate the parameters of an impact-spreading finger shaft for a grinder-mixer-dryer

When developing the design and technological scheme (Fig. 1), various shortcomings of existing feed grinders-mixers have been analyzed. At the same time, to reduce the energy intensity of the mixing process, the feed mass does not rise until it collapses, that is, after a certain feed, the feed mass is moved by the fingers of the impact-spreading shaft to the end walls of the bunker. At the same time, this process eliminates the rise of the feed mass until it collapses, and this helps to reduce the power required for the grinding and mixing processes. In addition, the operation of the impact-spreading finger shaft ensures that a certain small portion of the mass is supplied under hot air and this helps to intensify the drying process of wet feed raw materials. In this case, the inclusion of an impact-spreading finger shaft in the design and technological scheme of the grinder-mixer-dryer ensures a reduction in the energy intensity of the grinding and mixing processes, as well as accelerating the drying process of wet feed raw materials.

The originality of this development is confirmed by patents of the Republic of Kazakhstan for inventions No. 35587, 36486. It should be noted that currently existing feed mixers operate without such a shaft. At the same time, the energy intensity of the mixing process is very high. This can be seen from the fact that a chain with a pitch of 50.8 mm is used to drive existing mixers. In the developed grinder-mixer-dryer, the drive successfully uses a 19-pitch chain, which is more efficient. In addition, when operating existing mixers, empty space is formed near the side walls, i.e. during operation, the volume of the mixer hopper is not fully utilized. To reduce the energy intensity of the mixing process, it is advisable to have an impact-spreading finger shaft in the designs of existing feed mixers.

Determining the peripheral speed of the finger impact spreader shaft contributes to the selection of its diameter. Therefore, as a result of theoretical and experimental studies, the main parameters of the impact-spreading finger shaft were determined. It should also be noted here that a special experimental study was carried out to determine the effect of the peripheral speed of the fingers on the spreading process. This experimental study was conducted previously [34]. In addition, a hypothesis has been proposed that the peripheral speed of the finger impact-spreading shaft should be equal to the critical destructive speed of some fragile feed raw materials, such as eggshells, and on the other hand, it should produce a smooth flow movement of the feed mass to the end walls of the grinder-mixer-dryer. Experimentally determining the critical breaking speed of eggshells presented some difficulties, so theoretical studies were carried out to determine this speed.

When the finger impact-spreading shaft operates, in addition to moving the feed mass, an impact action is performed on the eggshell. At the same time, the finger impact-spreading shaft crushes the eggshells. To determine the destruction rate of eggshells, we conducted experimental studies. In this case, the appearance of cracks began when the eggshell fell from a height of 0.15 m (Fig. 2, *a*). However, we were unable to accurately determine the velocity of an eggshell falling from a given height. Therefore, a theoretical study was carried out to obtain an analytical expression to determine the critical destruction rate of eggshells (7). It should be noted here that the obtained result of the critical impact speed for breaking an eggshell, equal to 1.66 m/s, is compared with the impact speed in a hammer crusher, which is 60 m/s [35]. From this, it is clear that the

use of an impact-spreading pin shaft provides a sufficiently lower impact speed to break the eggshells as required, which is significantly less energy-intensive than the higher speeds obtained through a hammer crusher. This also confirms the effectiveness of the results obtained. As a result of our research, the resulting analytical expression is aimed at determining the critical destruction speed of brittle materials, i.e. this is some limitation for the application of the results of theoretical research. On the other hand, a theoretically determined speed ensures smooth flow movement of feed raw materials during the operation of the grinder-mixer-dryer. It should be noted that in the studies carried out, the critical destructive speed of feed raw material particles was theoretically determined by means of the fingers of the impact-spreading shaft. However, the effect of the auger knives on the grinding of feed particles should also be noted. Therefore, the lack of a theoretical determination of the rate of destruction of particles of feed raw materials by means of an auger with knives has some drawbacks and this should be taken into account in subsequent theoretical studies to determine the parameters of the auger with knives. On the other hand, the theoretical determination of this speed provides a more accurate choice of the rotation speed of the finger impact spreader shaft. The calculation results based on the obtained critical values of the rate of destruction of eggshells showed that the rotation frequency of the finger impact-spreading shaft was equal to 52.86 min$^{-1}$. In addition, during operation, the finger impact spreader shaft must move the mass smoothly. Based on this condition, the shaft rotation speed was equal to 48.25 min$^{-1}$. From here it became clear that the rational value of the rotation speed of the finger impact-spreading shaft is 50 min$^{-1}$. Next, experimental studies were carried out with the established rotation speed of the finger impact spreading shaft. The results of experimental studies showed that within 15 minutes of operation of the grinder-mixer-dryer with a finger impact-spreading shaft, eggshells are crushed in accordance with the requirements, that is, 91 % of the crushed particles have dimensions of 1...5 mm (Table 3).

The results of the drying process study also showed that the rate of change in humidity was 26.54 % per hour. In this case, the moisture content of the feed mass reached from 39.5 % to 9 % in 1 hour 15 minutes (Fig. 6).

When studying the mixing process, it was found that the homogeneity of the feed mixture reached 91.3 % within 6 minutes of operation of the grinder-mixer-dryer. This shows that the grinder-mixer-dryer with a finger impact spreader shaft can be used as a mixer for preparing animal feed.

Special experimental studies have shown that the inclusion of a finger impact spreading shaft provides a reduction in power consumption by 10.24 %. Here, for more productive installations, the reduction in power consumption should be significant.

The results of experimental studies also showed the reliability of the obtained analytical expression. The difference between the theoretical and experimental values was insignificant within the range of 1.74...3.26 %.

The main feature of the conducted research should be noted that the finger impact-spreading shaft carries out in-line movement of the feed mass across the entire width of the bunker and additional destruction of fragile feed raw materials. Moving the feed mass across the entire width of the bunker can be done with two augers, but this complicates the design of the installation. In addition, the auger does not supply a certain portion of hot air, i.e. in this case, the intensity of the drying process is reduced. In our opinion, such a finger spreading shaft (drum) is widely used in the designs of existing mixer

dispensers that provide the preparation of complete feed mixtures and compound feeds. When studying the process of separating the leafy part of herbs, the same finger drum was installed above an inclined sieve. In this case, as a result of experimental studies carried out by a multifactorial experiment, the optimal value of the peripheral speed of the finger drum was determined from the condition that the finger drum does not scatter, but carries out in-line movement of pre-chopped hay. As a result of experimental studies, the optimal peripheral speed of the finger drum at the ends of the fingers was equal to 1.61 m/s, i.e. coinciding with the theoretical value of the peripheral speed of the impact-spreading finger shaft. Therefore, in this study, during experimental tests, it was decided to refine this speed as a result of laboratory tests. Here, the results of experimental studies showed the appropriate operation of the impact-spreading finger shaft to meet the requirements of in-line movement of mass, and increase the efficiency of the processes of grinding, mixing and drying wet feed raw materials.

In the conducted studies, the rational value of the peripheral speed of the impact-spreading finger shaft was determined according to two indicators, i.e. from the condition of destruction of fragile feed raw materials and continuous movement of feed mass under hot air for accelerated drying of wet feed. Therefore, the obtained rational value of the peripheral speed of the fingers of the impact-spreading shaft is stable and can be adequately used for distributor-mixers.

It should be noted that in the studies conducted, the critical destruction rate was determined for brittle materials. For more plastic materials, the rotation frequency of the finger impact spreader shaft can be determined from the condition of smooth movement of the feed mass according to formula (9). It is clear from this that the resulting analytical expression (7) is used to determine the rotation frequency of smaller brittle materials. This is a limitation of the obtained analytical expression (7) in its practical application.

In general, the impact-spreading finger shaft or drum can be widely used in the designs of existing feed mills. This may be a development of this study.

## 7. Conclusions

1. For the parallel flow of the processes of grinding, mixing and drying wet feed raw materials, a design and technological diagram of a laboratory installation has been developed, consisting of a hopper, a horizontal auger with knives, an impact-spreading finger shaft, pipes for supplying hot air and feed raw materials, as well as a hatch for unloading the finished product. In this case, an auger with knives crushes and moves feed raw materials in one direction, and the impact-spreading finger shaft ensures partial grinding of fragile feed raw materials, such as eggshells, and also ensures limited mass lifting and intensive processes of mixing and drying wet feed with uniform filling bunker installation. Drawing documentation was developed, a laser installation was manufactured, and experimental studies were carried out to justify the parameters.

2. As a result of special experiments, the beginning of the appearance of cracks in eggshells was determined when they fall from a height of 0.15 m. Therefore, this speed of impact of eggshells on a metal surface is the critical peripheral speed of the impact-spreading finger shaft, which ensures partial grinding of such fragile materials as eggshells. As a result of theoretical studies, an analytical expression was obtained that provides the determination of the impact speed of a material depending on the height of its fall. In this case, the value of the critical impact velocity for the destruction of an eggshell was determined and it is equal to 1.66 m/s.

3. The theoretical determination of the peripheral speed of the impact-spreading finger shaft corresponds to the optimal values of the peripheral speed of the finger drum for separating the leaf part of grass from pre-shredded hay. This value was determined from the condition of in-line movement of the mass to the other side of pre-shredded hay moving along an inclined sieve. Therefore, an experimental study was carried out on this peripheral speed of the impact-spreading finger shaft. Special experiments determined the critical force of destruction under static conditions, equal to 2.8449 N, as well as the density of the eggshell, equal to 1,595 kg/m$^3$. The results of experimental studies showed the effective processes of grinding, mixing and drying wet feed raw materials. Moreover, within 15 minutes of operation of the installation, the wet eggshell was crushed in accordance with the requirements. Uniformity reached up to 90 % within 4–6 minutes of operation, and the drying process proceeded at a rate of 26.54 % per hour. All this proves the effectiveness of the processes of grinding, mixing and drying wet food, and also confirms the reliability of theoretical research.

## 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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The manuscript has no associated data.

## Use of artificial intelligence

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

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