Article

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Featured Application

The developed feed mixer-distributor equipped with a leveling–mixing device can be applied in small-scale livestock farms for the preparation and distribution of total mixed rations with reduced energy consumption and improved mixing efficiency. The proposed dual-circuit mixing technology ensures accelerated achievement of mixture uniformity while decreasing the power required for the mixing process. The developed design may be used in farms with up to 100 head of cattle and can contribute to improving the energy efficiency of feed preparation systems in small and medium-sized livestock enterprises.

Abstract

A hypothesis was proposed that continuous dual-circuit mixing can be achieved by equipping a feed mixer-distributor with two leveling–mixing finger shafts, which, after lifting the feed mass to a certain height, collect it in the central part of the hopper and divide it into two flows directed toward the end walls of the hopper. In this case, continuous dual-circuit mixing is performed during each rotation of the leveling–mixing shaft. A structural and technological scheme, engineering documentation, and an experimental prototype of the feed mixer-distributor were developed. The machine consists of a 3.0 m^3 hopper, two horizontal augers, two leveling–mixing finger shafts, a loading conveyor, and a drive mechanism. Theoretical investigations were conducted, and analytical expressions were obtained to determine the circumferential velocity of the fingers of the leveling–mixing device, which should ensure the movement of the feed mixture without scattering and provide the release of the feed mass from the finger surface at a finger rotation angle of 30°. Calculations based on the obtained analytical expressions showed that the critical circumferential velocity of the fingers was 0.8 m/s, while the rotational speed of the finger shaft was 19 min^{-1}. An analytical expression was also obtained to determine the velocity of feed mixture movement along the finger surface. Based on the calculations, the optimal value of this velocity was found to be 0.7 m/s. This value corresponds to the rational velocity of feed mixture transportation toward the end walls of the hopper. Laboratory experiments were carried out using the feed mixer-distributor at a leveling–mixing finger shaft rotational speed of $n = 20$ min^{-1}. The optimal mixing time required to achieve the target mixture uniformity was 5.5 min, which is 15.4% lower than that of existing machines. Comparative experiments also showed that incorporating the leveling–mixing device into the feed mixer-distributor reduced the power consumption of the mixing process by 34%.

Keywords: dual-circuit mixing; leveling–mixing device; circumferential velocity; mixture uniformity; feed mixture transportation velocity; finger shaft

1. Introduction

The preparation and distribution of feed mixtures at dairy and fattening farms are among the most labor-intensive processes in livestock production.

These technological operations are performed using modern feed mixer-distributors with hopper capacities ranging from 4.0 to 30.0 m³ [1].

In all feed mixer-distributors equipped with horizontal augers, the mixing process is carried out by lifting the feed mass until it collapses under gravity. The horizontal auger collects the feed mixture in the central part of the hopper, after which the mass is lifted upward. When the maximum lifting height is reached, the feed mixture collapses downward in large portions. During the lifting stage, the horizontal auger experiences a significant resistance torque, resulting in increased energy consumption of the mixing process.

In addition, after the feed mass collapses in large portions, the auger transports these portions back to the central zone of the hopper. As a result, the process of achieving the required mixture uniformity becomes prolonged and is accompanied by increased energy consumption.

Thus, the use of the above-mentioned technological mixing process represents one of the main disadvantages of existing feed mixer-distributors equipped with horizontal augers.

Therefore, studies aimed at reducing the energy consumption and mixing duration are an important step toward the development of more advanced agricultural machinery.

However, the problem of reducing the energy consumption of compact horizontal feed mixer-distributors by controlling the internal redistribution of moist fibrous feed mass remains insufficiently studied. Therefore, the present study focuses on the development and experimental evaluation of a leveling–mixing device intended to organize continuous dual-circuit mixing inside the hopper.

2. Review of Scientific and Technical Literature

Currently, in the Republic of Kazakhstan, the majority of livestock is concentrated in household farms and small-scale farming enterprises. More than 70–80% of such farms keep up to 50–100 head of cattle and up to 500 sheep, which creates a stable demand for compact machinery intended for feed preparation and distribution [1]. At the same time, most commercially manufactured feed mixer-distributors are designed for large livestock farms and are characterized by hopper capacities exceeding 6.0 m³ and high installed drive power [1,2].

Analysis of the scientific literature shows that feed mixer-distributors equipped with horizontal and vertical auger working bodies are the most widely used. In such machines, the mixing process is performed by lifting the feed mass followed by its collapse under gravity [1].

For example, in the Trioliet Solomix 2-12 ZK feed mixer-distributor with a hopper capacity of 12 m³ and two vertical augers, the mixing process is also carried out by lifting the feed mass until collapse, while the installed drive power reaches 60 kW, indicating the high energy consumption of this mixing mechanism [2]. A similar principle is implemented in compact machines with hopper capacities of approximately 4 m³ and a single horizontal auger, where the same energy and technological disadvantages of the mixing process remain [3].

Patent studies indicate the existence of alternative structural solutions, including feed mixer-distributors with rotating hoppers. However, such designs are generally intended for mixing bulk materials and preparing compound feed and do not ensure effective mixing of moist fibrous feed materials [4].

According to zootechnical requirements, the uniformity of feed mass distribution along the feeding front should be at least 85% for cattle and at least 90% for pigs [5]. Important parameters in selecting feed mixer-distributors include hopper capacity, overall dimensions, power consumption, the presence of weighing systems, self-loading capability, and operational stability [6]. In addition, several studies have identified mixture uniformity, feed preparation time, the absence of “dead zones”, and complete hopper unloading as key performance criteria [7].

Experimental studies of the grinding and mixing processes of fibrous feed materials have shown that many commercially available feed mixer-distributors do not provide the required grinding quality. It was established that during the operation of ISRK-12 mixers for 10–50 min, the average particle length reached 50 mm, indicating the low efficiency of such machines in processing long-stem feed materials [8].

Several studies have investigated the mixing processes of grain feed components in horizontal auger mixers. It was found that the minimum mixture non-uniformity (1.8–4.1%) was achieved at a shaft rotational speed of 30–35 rpm and a mixing duration of 3–4 min. However, these results are mainly applicable to loose grain materials and cannot be directly applied to moist and fibrous feed mixtures [9].

Recent studies have shown that the design of working bodies and the kinematic parameters of total mixed ration (TMR) mixers have a significant influence on mixing uniformity, material circulation, and energy consumption. Wang et al. [27] developed and tested a segmented spiral TMR mixer and demonstrated that the geometry of the spiral working body affects the redistribution of feed components and the stability of the mixing process. Li et al. [31] experimentally investigated power consumption during the kneading and cutting of fibrous plant material in a horizontal TMR mixer and confirmed that the operating mode of the working bodies is one of the main factors determining the energy intensity of the process.

Theoretical investigations of the mixing process demonstrated the significant influence of longitudinal feed mass distribution along the hopper length on mixture uniformity. Analytical relationships describing the probability distribution of components along the hopper length were obtained, confirming the necessity of controlling feed mass redistribution inside the mixing chamber [10]. At the same time, the developed mathematical models are generally intended for loose materials and have limited applicability to moist fibrous feeds [11].

Moreover, recent studies indicate that fibrous feed mixtures require more specific approaches than loose granular materials because their movement inside the hopper is affected by particle length, moisture content, friction, and the interaction between the feed mass and the working bodies. Nikitin et al. [29] proposed an image-based approach for assessing the homogeneity of forage mixtures using cattle rations as an example, which confirms the importance of objective evaluation methods for feed mixture uniformity. Tian et al. [32] also showed that the loading and mixing characteristics of self-propelled TMR mixers can be studied using simulation and performance testing, which is important for substantiating the operating parameters of feed preparation machines.

Reference [12] presents the results of theoretical and experimental studies aimed at substantiating the parameters and kinematic modes of a grinder–mixer–dryer for moist shell waste and other meat-and-bone feed materials. In this study, improved leveling efficiency after a certain lifting height of the material was achieved compared with the operation of the grinder–mixer–dryer without a leveling device.

Reference [13] discusses the technological requirements for feed mixer-distributors intended for small farms. A feed mixer-distributor design capable of feed dosing for different animal groups was presented, and comparative technical and economic indicators of feed mixer-distributors were provided.

In study [14], a feed mixer-distributor capable of simultaneous feed distribution, grinding, and mixing was proposed, and its main design and operating parameters were optimized. In this design, long-stem feed materials are captured and ground by knives due to the resulting relative motion, while mixing is performed by the screw surfaces of rotating augers through reciprocating movement.

Study [15] formalized the influence of several mechanization parameters on the ergonomics and manufacturability of feed loading and distribution processes. It was established that some feed distributors are characterized by difficult and low-quality feed distribution, especially at the initial unloading stage, leading to additional labor costs.

The objective of study [16] was to improve the efficiency of feed mixture preparation by optimizing the working bodies and operating parameters of a feed mixer-distributor. Theoretical and experimental studies were carried out to determine the design parameters of the machine; however, insufficient attention was paid to feed grinding quality.

In study [17], vibratory mixers were proposed for achieving uniform mixing of feed components. The operating parameters of a trough-type vibratory mixer were determined, and the influence of feed rate, vibration amplitude, and vibration frequency on mixture uniformity was investigated.

Reference [18] presents a screw feed mixer equipped with an agitator made in the form of an auger with rod elements. This design improves feed mixing by generating a turbulent flow and reduces the energy consumption of the mixing process. The agitator and auger are manufactured separately and connected by a threaded joint, while the division of the housing into receiving and working chambers enables the replacement of the agitator for mixing feeds of different fractions.

In study [19], a three-auger mixer-distributor with an adjustable inclination angle of the upper augers was developed. The inclination of the upper augers allows the feed mass transported by the lower auger to be diverted from the hopper wall and lifted upward while simultaneously mixing the material. The power required to drive the mixer is consumed for lifting the product within the hopper, overcoming friction forces between the product and the hopper walls, overcoming friction between the feed mixture and the auger surface, mixing the product, and overcoming friction in bearings and transmission mechanisms.

Further development of TMR mixer designs is also aimed at improving the movement of fibrous feed materials inside the mixing chamber. Chen et al. [30] optimized and experimentally tested a double-helix TMR mixer for silage straw feed, showing that the configuration of the mixing working bodies affects both the quality of feed preparation and the technological stability of the process. Similar attention to the combined processes of grinding and mixing was given by Iskakov and Gulyarenko [28], who investigated mixing uniformity in a feed preparation device equipped with impact-mixing mechanisms.

The authors emphasize that feed mixtures cannot be considered as conventional loose materials, and existing mixing models have fundamental limitations [20].

According to data published in the Journal of Dairy Science, the optimal particle size of roughage in total mixed rations (TMR) should be within the range of 30–50 mm to ensure uniform component distribution [21].

It has also been established that non-uniformity of total mixed rations leads to selective feeding behavior, fluctuations in dry matter intake, and reduced nutrient utilization efficiency [22].

Modern studies are also focused on the automation of feeding processes. It has been shown that the implementation of automatic and mobile feeding systems can increase feeding frequency and reduce labor costs; however, the efficiency of such systems directly depends on the stability and uniformity of the prepared feed mixture [23].

Thus, the analysis of recent studies shows that the improvement of feed mixer-distributors is mainly associated with optimization of auger geometry, working body configuration, mixing time, power consumption, and methods for evaluating mixture homogeneity [27–32]. However, the problem of reducing energy consumption by preventing uncontrolled collapse of the lifted feed layer and by organizing continuous dual-circuit redistribution of moist fibrous feed mass inside the hopper remains insufficiently studied. This confirms the relevance of developing a leveling–mixing device that redirects the feed mass toward the end walls of the hopper after a limited lifting height is reached.

3. Research Aim and Objectives

The aim of this study was to develop a compact feed mixer-distributor equipped with a leveling–mixing device that provides continuous dual-circuit feed mixing, and to conduct theoretical and experimental studies to substantiate the rational kinematic modes of the process under consideration.

The objectives of the study were as follows:

– to substantiate the structural and technological scheme of a compact feed mixer-distributor equipped with two leveling–mixing finger shafts that provide continuous dual-circuit feed mixing;

– to determine the circumferential velocity of the fingers of the leveling–mixing shaft and establish a theoretical relationship between the velocity of feed mass movement toward the end walls of the hopper and the finger rotation angle;

– to conduct laboratory experiments to analyze the operation of the kinematic modes and determine mixture uniformity depending on the operating time of the feed mixer-distributor equipped with the leveling–mixing device.

4. Materials and Methods

A new leveling–mixing device was incorporated into the design of the feed mixer-distributor.

The object of the study was the technological process of feed mass movement toward the end walls of the hopper and the dual-circuit mixing process performed by the leveling–mixing finger shaft.

In existing machines, the mixing process is carried out by lifting the feed mass until its collapse. During this process, the blades of the horizontal auger are subjected to significant loading while lifting a large volume of feed mixture. In addition, the lifted mass collapses toward the end walls of the hopper in large portions, after which the horizontal auger transports these large portions back to the center of the hopper. This mechanism results in a prolonged mixing process.

To eliminate the above-mentioned disadvantages, a hypothesis was proposed stating that, after a slight lifting of the feed mass, it should be divided into two flows directed toward the end walls of the hopper. Subsequently, the horizontal auger should transport the mass back to the central part of the hopper. This process is achieved through the operation of the newly developed leveling–mixing finger shaft. In this case, the feed mixture is not lifted to the point of collapse, and the dual-circuit circulation of the mass is carried out in small portions during each rotation of the finger shaft. This contributes to reducing energy consumption and accelerating the mixing process.

As a result of the theoretical investigations, the critical rotational speed of the finger shaft was determined based on the condition of free release of the fingers from the monolithic feed mass without scattering the material and without carrying it into the next rotation cycle of the finger shaft.

The theoretical analysis of the mixing process performed by the finger shaft resulted in an analytical expression for determining the velocity of feed mass movement toward the end walls of the hopper. A dynamic analysis method was applied in solving this problem.

During the experiments, the rotational speed of the leveling–mixing shaft corresponded to the theoretically determined values.

Analysis of the operating mode of the finger shaft confirmed the rationality of the selected kinematic mode. The finger shaft transported the feed mass without scattering, while free release of the fingers from the monolithic feed mixture was ensured.

Experimental studies were conducted to determine mixture uniformity depending on mixing time. The coefficient of variation of the control component was determined based on the analysis of 10 samples.

The optimal rotational speed of the finger shaft was determined when the mixing uniformity reached 90% or higher. The mass of feed components was measured using an F-1976 electronic dynamometer. The samples and control components were weighed using MW-II scales manufactured by CAS (South Korea).

Comparative experiments were carried out using the feed mixer-distributor both with and without the leveling–mixing device. In these experiments, the resistance torque on the main gearbox shaft was determined. A TRK-0.5 strain gauge sensor and an ACD-1R-0.5 electronic dynamometer was used to measure the resistance torque.

5. Results of Studies on the Development of a Compact Feed Mixer-Distributor Equipped with a Leveling–Mixing Device Providing Reduced Energy Consumption and Accelerated Mixing Process

5.1. Substantiation of the Structural and Technological Scheme of the Compact Feed Mixer-Distributor

Analysis of existing feed mixer-distributor designs showed that their mixing process is characterized by high energy consumption and long mixing duration. This is because, during operation, the feed mixture is lifted until collapse occurs. The lifting of the feed mass is performed by the auger blades, resulting in a high resistance torque. In addition, the feed mass collapses in large portions, which are then transported back to the center of the hopper. As a result, the mixing process proceeds slowly and with high energy consumption.

In addition, all the above-mentioned feed mixer-distributors have hopper capacities ranging from 4 to 30 m^3, and only in recent years have compact feed mixer-distributors with hopper capacities below 4 m^3 begun to be developed [1].

At present, a significant number of farms are focused on livestock production. For example, in the Republic of Kazakhstan, approximately 70% of livestock farms keep up to 100 head of cattle.

Therefore, a feed mixer-distributor equipped with a leveling–mixing device is being developed within the framework of the program-targeted funding project IRN BR23992300, “Development and improvement of technical means and technological equipment ensuring the implementation of scientifically substantiated livestock production technologies”, under the project activity “Feed mixer-distributor for farms with up to 100 head of cattle”. The proposed machine performs the technological process using a new operating principle that reduces energy consumption and accelerates the mixing process.

Considering that the daily feed mixture requirement for 100 head of cattle is approximately 2300–2400 kg, the mass of feed mixture for a single feeding cycle is about 800 kg. For a feed mixture consisting of chopped hay, silage or haylage, and compound feed with a bulk density of 350 kg/m^3, the required hopper capacity of the feed mixer-distributor is 3.0 m^3.

To reduce the energy consumption of the mixing process, a hypothesis was proposed stating that the lifted feed layer should not be raised to the point of collapse. Instead, after reaching a certain lifting height, the feed mass should be intentionally redirected from the central zone toward the end walls of the hopper. This approach makes it possible to reduce energy losses associated with uncontrolled collapse of the feed layer and to provide more uniform distribution of feed components.

This process can theoretically be implemented using an auger with left- and right-handed flights. However, since the auger transports the feed mass mainly along one wall of the hopper, a dead zone remains along the opposite wall where mixing does not occur. This drawback can be eliminated by installing a second auger in the upper part of the hopper, although this solution complicates the design and increases the machine cost.

In existing machines, blades are installed in the middle section, while the auger flights change from left-handed to right-handed from the central part of the auger. This design ensures transportation of the feed mass toward the center of the hopper. However, the collected feed mass is first lifted to a certain height and then collapses downward. In this case, the feed mass collapses in large portions and is transported back to the center of the hopper in the same large portions, which increases the mixing duration.

When the feed mass is lifted to the point of collapse, the auger shaft experiences high resistance from the lifted material, resulting in increased power consumption for driving the auger and higher energy intensity of the mixing process.

To eliminate the above-mentioned disadvantages of existing feed mixer-distributors, a new mixing technology is proposed. The essence of this process is that, after a slight lifting of the collected feed mass, it should be divided into two flows and transported toward the end walls of the hopper. In this case, the mixing process is performed using a new principle, namely continuous dual-circuit mixing.

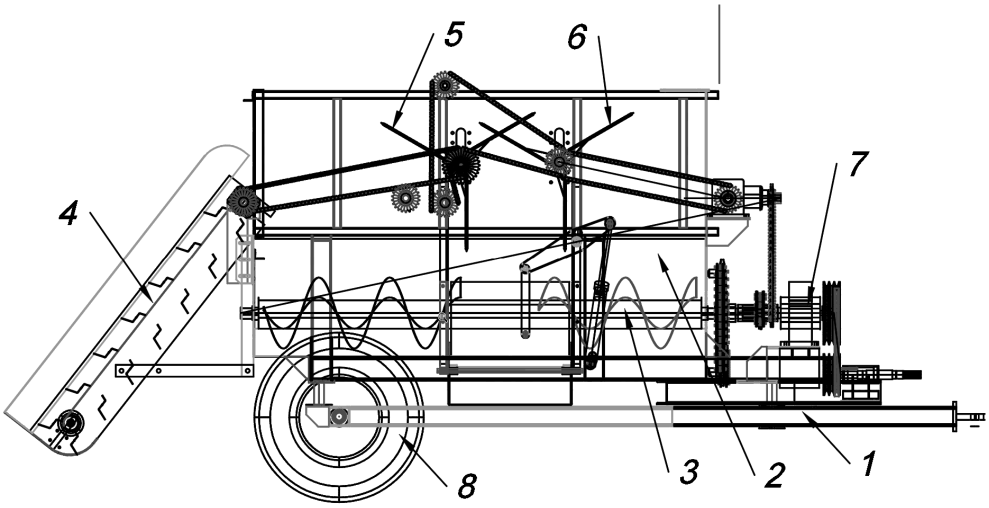
To implement the proposed method, two leveling–mixing shafts were incorporated into the design of the feed mixer-distributor. During operation, these shafts divide the feed mass into two flows and transport it toward the end walls of the hopper. Each shaft is equipped with three rows of fingers; therefore, during each shaft rotation, the feed mass is transported toward the end walls three times. This contributes to reducing energy consumption and accelerating the mixing process.

Based on the above considerations, a feed mixer-distributor was developed consisting of a frame (1), a hopper (2) with a capacity of 3.0 m^3, a horizontal auger (3), a loading conveyor (4), leveling–mixing shafts (5, 6), drive mechanisms (7), and wheels (8).

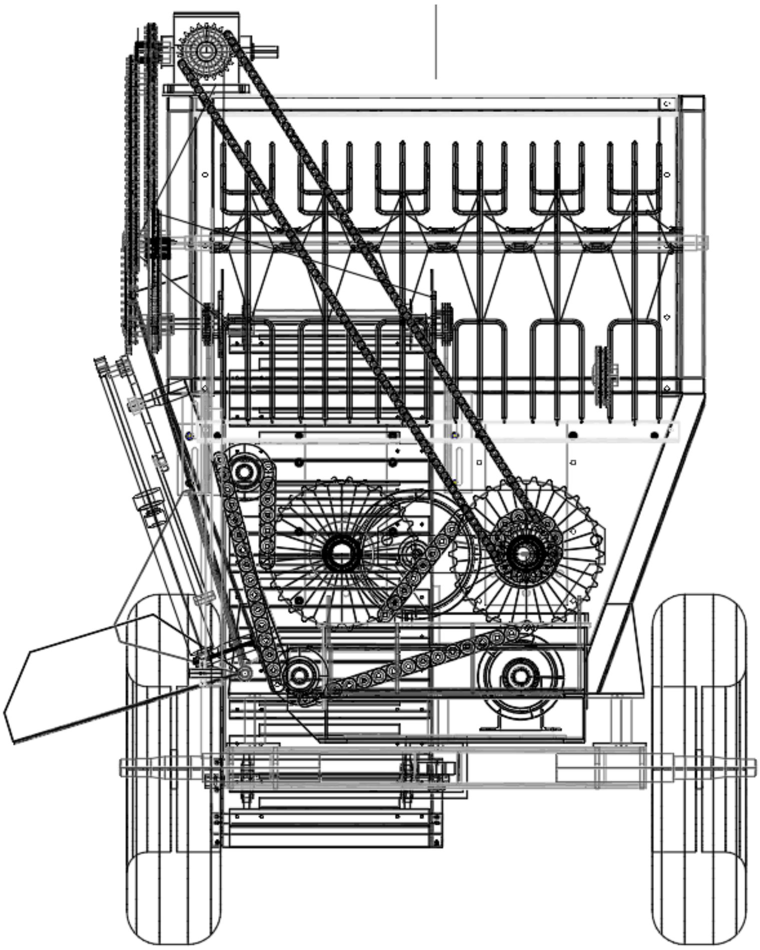
The hopper of the machine is mounted on three load cells, which ensure accurate loading of each feed component according to the feeding ration.

At present, Patent of the Republic of Kazakhstan No. 35587 for the invention "Feed mixer-distributor" has been obtained for the feed mixer-distributor design equipped with the new leveling device.

Thus, a new feed mixer-distributor equipped with loading and leveling–mixing devices is being developed to reduce energy consumption and accelerate the mixing process of feed mixture components.



(a) Side view



(b) End view

Figure 1. Structural and technological scheme of the feed mixer-distributor. 1 – frame; 2 – hopper; 3 – horizontal auger; 4 – loading conveyor; 5, 6 – leveling–mixing shafts; 7 – drive mechanism; 8 – wheel.

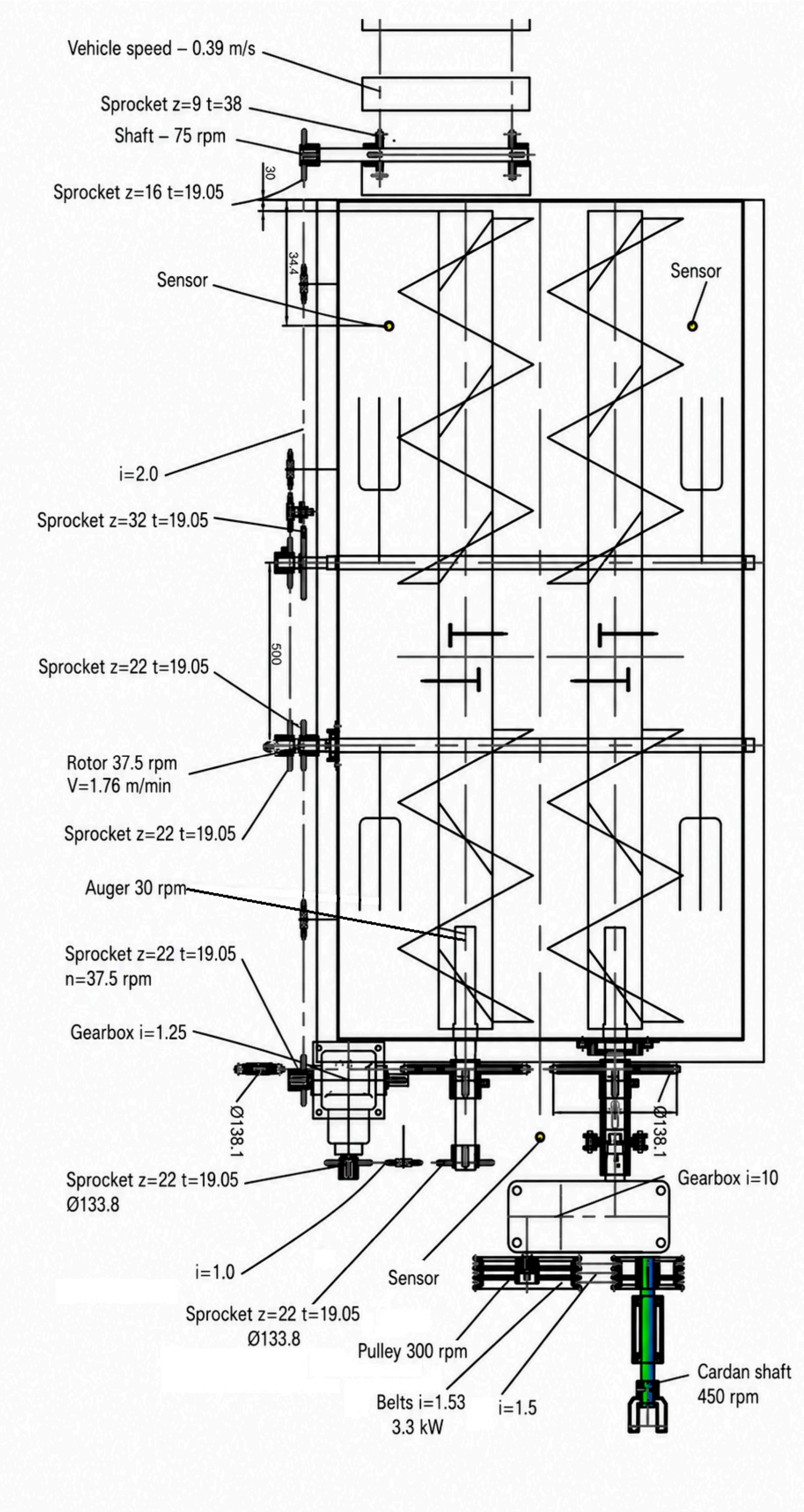


Figure 2. Kinematic scheme of the feed mixer-distributor At present, the engineering documentation has been developed, and an experimental prototype of the compact feed mixer-distributor has been manufactured (Figure 3).

Figure 3. General view of the experimental prototype of the compact feed mixer-distributor Factory tests of the feed mixer-distributor were carried out. It was established that all mechanisms operated under the specified operating conditions, and the machine was confirmed to be ready for field testing and experimental investigations.

5.2. Theoretical Determination of the Rotational Speed of the Leveling–Mixing Finger Shaft

According to the structural and technological scheme, the horizontal auger collects the feed mass in the central part of the hopper, and after a certain lifting height is reached, the leveling finger shaft transports the feed mixture toward the end walls of the hopper. In this case, the feed mixture is not lifted to the point of collapse, which contributes to reducing the energy consumption and mixing time required to achieve the target mixture uniformity.

When substantiating the parameters of the finger shaft to ensure proper operation of the leveling device, it is important to determine the rational rotational speed of the shaft.

At the rational rotational speed, the fingers should transport the feed mass without scattering it, and at a certain inclination angle, the feed mixture should separate from the finger surface, thereby ensuring accelerated dual-circuit mixing of the feed mass in cooperation with the horizontal auger (Figure 4).

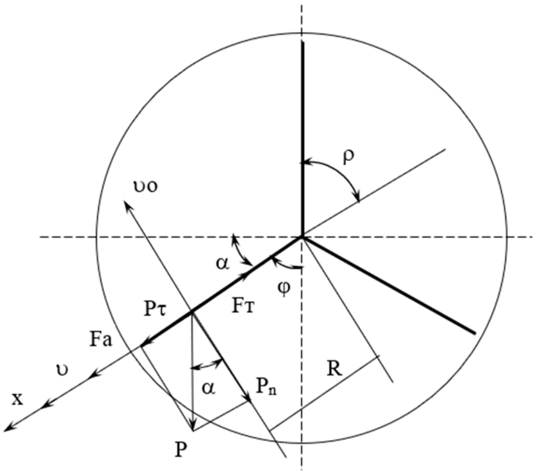


Figure 4. Diagram of the forces acting on the feed mass located on the surface of the shaft fingers during the movement of the feed mixture toward the end walls of the hopper Special experiments showed that the feed

mixture begins to slide from the surface of a metal plate at an angle of $\alpha = 38°$. In this case, tg38° = 0,78, therefore, the sliding friction coefficient of the feed mixture on the metal surface is $f = 0,78$.

However, as the angle α decreases, the friction force increases, i.e., the tangential component of the gravitational force becomes smaller than the friction force. For rational operation of the finger shaft, the fingers should complete the transportation of the feed mass at an angle of $\alpha = 30°$, meaning that at this angle the fingers should freely separate from the monolithic feed mass.

At an angle of $\alpha = 30°$, the friction force exceeds the tangential component of the gravitational force of the feed mixture by a certain value. In this case, it can be hypothesized that, at $\alpha = 30°$, the fingers freely detach from the monolithic feed mass, i.e., the difference between the above-mentioned forces is equal to the centrifugal force F_a determined by the circumferential velocity υ_o.

The value of the circumferential velocity υ_o or the rotational speed of the finger shaft can be determined by considering the equilibrium of the system under static conditions.

It is well known that when inertial force is introduced into the system, all equations of statics can be applied [24].

In our opinion, a certain critical value of the circumferential velocity or rotational speed of the finger shaft may be considered a rational operating value. This is because, during operation, the rotating fingers generate vibrations in the system, resulting in a reduction of the friction coefficient.

Based on the above considerations, the equilibrium equation of the forces acting on the feed mixture at a finger angle of $\alpha = 30°$ can be written as follows:

$$F_x = F_a + P\tau - F_T = 0 \qquad (1)$$

where F_a – is the centrifugal inertial force acting on the feed mixture with mass m, N;

$P\tau$ – is the tangential component of the gravitational force, N;

F_T – is the friction force, N.

$$\frac{m\upsilon_o^2}{R} + m\,g\,sin\alpha - m\,g\,cos\alpha\,f = 0,$$

$$\frac{\upsilon_o^2}{R} = fg\,cos\alpha - g\,sin\alpha \qquad (2)$$

where m is the mass of the feed mixture located on the finger surface, kg;

υ_o is the circumferential velocity of the finger shaft, m/s.

From Equation (2), the circumferential velocity of the finger shaft can be determined as follows:

$$\upsilon_o = \sqrt{gR(fcos\alpha - sin\alpha)} \qquad (3)$$

From Equation (3), the minimum rotational speed of the leveling–mixing finger shaft can be determined from the known value of the circumferential velocity υ_o:

$$\upsilon_O \geq \frac{\pi n}{30} R,$$

$$n \geq \frac{30\upsilon_O}{\pi R}. \qquad (4)$$

For the planned radius of $R = 0,4$ m, at $\alpha = 30°$, $f = 0,78$, the calculated circumferential velocity is $\upsilon_o = 0,8$ m/s, and the rotational speed of the leveling–mixing finger shaft is $n = 19$ min^{-1}. In practice, these calculated values should be considered rational operating values. As noted above, during rotation of the finger shaft, vibrations generated by the rotating fingers reduce the friction coefficient, allowing the fingers to freely release from the monolithic feed mass while ensuring the movement of the mass toward the end walls of the hopper.

During operation of the leveling–mixing shaft, at finger rotation angles of $\alpha = 34…45°$, the feed mass should move along the finger surface under the action of centrifugal forces. This movement should have a rational value; that is, it should not be excessively rapid, should not scatter the feed mass, and at the minimum angle of $\alpha = 30°$, the feed mixture should freely slide from the finger surface.

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To analyze the motion of the feed mass on the finger surface, the following differential equation is formulated:

$$m\frac{dv}{dt} = F_a + P_\tau - F_T, \tag{5}$$

$$m\frac{dv}{dt} = \frac{mv_O^2}{R} + mg\,sin\,\alpha - mg\,cos\,\alpha \cdot f,$$

$$\frac{dv}{dt} = \frac{v_O^2}{R} + g\,sin\,\alpha - gf\,cos\,\alpha$$

$$dv = \left[\frac{v_O^2}{R} + g(sin\,\alpha - f\,cos\,\alpha)\right]dt. \tag{6}$$

The process of feed mass movement occurs within the range of variation of the angles φ and α. In this case, the time interval t_φ can be determined depending on the rotation of the fingers through the angle φ:

$$t_\varphi = \frac{60}{n} \cdot \frac{\varphi}{360} = \frac{\varphi}{6 \cdot \rightleftarrows n} = \frac{\varphi}{6 \rightleftarrows \cdot \frac{30v_O}{\pi \cdot R}} = \frac{\pi \cdot R \cdot \varphi}{180 \cdot v_O}. \tag{7}$$

To determine the velocity of movement along the finger surface, Equation (6) should be integrated over the velocity range from 0 to v_m and over the time interval from t to t_φ:

$$\int_0^{v_m^0} dv = \left[\frac{v_O^2}{R} + g(sin\,\alpha - f\,cos\,\alpha)\right]\int_0^{t\varphi} dt. \tag{8}$$

$$v_m = \left[\frac{v_O^2}{R} + g(sin\,\alpha - f\,cos\,\alpha)\right]t_\varphi. \tag{9}$$

Substituting this value into Equation (9), we obtain:

$$v_m = \left[\frac{v_O^2}{R} + g(sin\,\alpha - f\,cos\,\alpha)\right] \cdot \frac{\pi \cdot R \cdot \varphi}{180 \cdot v_O},$$

$$v_m = \frac{\pi \cdot \varphi \cdot v_O}{180} + \frac{g \cdot \pi \cdot R\varphi}{180 \cdot v_O}(sin\,\alpha - f\,cos\,\alpha). \tag{10}$$

Thus, an analytical expression was obtained for determining the velocity of feed mass movement along the finger surface of the leveling–mixing shaft.

As noted above, v_o = 0.8 m/s, R = 0.4 m, and f = 0.78. By substituting different values of α and φ into the obtained Equation (10), the corresponding calculations were performed.

Figure 5 shows the variation in the feed mass movement velocity v_m depending on the change in angle α. In the calculations, the value of angle φ was substituted according to the variation of angle α. For example, at $\alpha = 30°$, the corresponding value was $\varphi = 60°$.

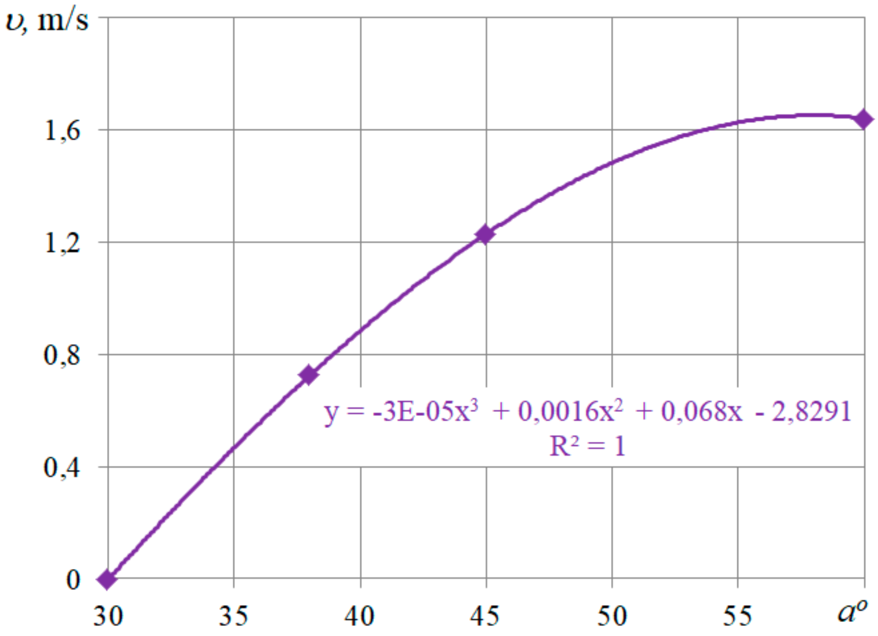

Figure 5. Calculated values of the feed mass movement velocity along the surface of the fingers of the leveling–mixing shaft.

In this case, as the angle φ increases, the value of angle α decreases, resulting in a reduction in the velocity of feed mass movement along the finger surface. This is due to the fact that, with increasing angle α, the tangential component of the gravitational force P increases.

During operation of the leveling–mixing finger shaft, the working value of the feed mass movement velocity toward the end walls of the hopper can be considered the velocity corresponding to α = 38°. In this case, the friction force becomes equal to the tangential component of the gravitational force acting on the feed mixture. Therefore, the movement of the feed mass along the finger surface is caused only by the centrifugal force. In addition, with further reduction of angle α, the feed mass should separate from the finger surface. The graph shows that at $\alpha = 38°$, the feed mass movement velocity is υ_m = 0.725 m/s, which is close to the calculated circumferential velocity of the fingers.

At $\alpha > 40°$, the feed mass is directed toward the monolithic feed layer, and due to the velocity υ_m, the feed mixture becomes partially compacted. Thus, the rational value of the feed mass movement velocity along the finger surface, at which the feed mixture freely moves toward the end walls of the hopper, is υ_m = 0.7 m/s. This confirms the validity of the obtained analytical expression.

If the circumferential velocity υ_b exceeded 0.8 m/s, the value of υ_m would increase, leading to scattering of the feed mass.

Therefore, during the development of the structural and technological scheme of the feed mixer-distributor, a rotational speed of n = 20 min^{-1} was selected as the operating mode of the leveling–mixing shaft.

Based on the above, it can be concluded that the main advantage of incorporating the leveling–mixing shaft into the feed mixer-distributor design is the reduction of energy consumption and the acceleration of the mixing process.

Therefore, to confirm the validity of the developed structural and technological schemes and the theoretical investigations, experimental studies should be conducted.

5.3. Laboratory Experiments for Analyzing the Operation of the Kinematic Modes and Determining Mixture Uniformity Depending on the Operating Time of the Feed Mixer-Distributor Equipped with a Leveling–Mixing Device

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5.3.1. Substantiation of the Kinematic Modes of the Leveling–Mixing Device

Laboratory experiments of the experimental prototype of the feed mixer-distributor were carried out on the territory of the research center.

For the experiments, 100 kg of hay, 200 kg of silage, and 50 kg of crushed grain and wheat were prepared.

During the preliminary testing of the feed mixer-distributor, the PTO rotational speed was 450 min^{-1}, the auger rotational speed was $n_r = 30$ min^{-1}, and the rotational speed of the leveling finger shaft was $n_s = 20$ min^{-1}.

During operation of the feed mixer-distributor, after a certain lifting height of the feed mass is reached, the leveling–mixing finger shaft divides the mass into two flows. After rotating from the vertical position, the fingers begin transporting the feed mass toward the end walls of the hopper. This process occurs during each rotation of the finger shaft; therefore, continuous dual-circuit mixing takes place, which should contribute to accelerated achievement of the required mixture uniformity.

The main performance indicator for all feed mixer-distributors is the ability to ensure the required mixture uniformity. According to zootechnical requirements, the mixture uniformity should be 90% for cattle, 75–80% for sheep, and at least 80% for pigs [25]. Therefore, during the experimental investigations, experiments were conducted to determine the uniformity of the feed mixture depending on the operating time of the feed mixer-distributor.

Initially, experiments were carried out to determine the uniformity of feed mass distribution along the feeding front.

For the experiments, 70 kg of hay, 210 kg of silage, and 42 kg of crushed grain were loaded into the hopper of the feed mixer-distributor. The total feed mixture mass was 322 kg (Figure 6).

After six minutes of operation of the feed mixer-distributor, the feed mixture was unloaded onto a level surface to determine the mass distribution along the feeding front (Figure 7).

Figure 6. Fragment of loading feed components into the hopper of the feed mixer-distributor using the conveyor.

Figure 7. Fragment of the experimental technological process of unloading the feed mixture onto the feeding table.

The mass of feed per linear meter of the feeding front was determined from the unloaded feed mixture (Table 1).

Table 1. Results of feed mass distribution along the feeding front.

n	Feed mass per linear meter, m_i *kg*	$(m_i - m_{avg})$	$(m_i - m_{avg})^2$
1	12,7	0,2	0,04
2	13,2	0,3	0,09
3	12,6	0	0
4	13,5	0,6	0,36
5	13,7	0,8	0,64
6	12,8	0,1	0,01
7	11,8	1,1	1,21
8	13,5	0,6	0,36
9	12,4	0,5	0,25
10	12,6	0,3	0,09
	∑ 129,1		∑ 3,05

$m_{avg} = 12{,}9$

$$\sigma = \sqrt{\frac{(m_i - m_f)^2}{n}} = \sqrt{\frac{3{,}05}{9}} = 0{,}582.$$

The coefficient of variation is determined using the following equation:

$$\upsilon = \frac{\sigma \cdot 100}{m_f} = \frac{0{,}582 \cdot 100}{12{,}9} = 4{,}5\%.$$

Uniformity of feed mass distribution:

$$O = 100 - \upsilon = 100 - 4{,}5 = 95{,}5\%.$$

The results of the laboratory experiments showed that the experimental prototype of the feed mixer-distributor performs the technological process of feed mass distribution along the feeding front in accordance with zootechnical requirements and ensures high-quality distribution with a uniformity exceeding 90%.

It should also be noted that, with the discharge gate fully opened, the average mass of unloaded feed was 12.9 kg.

At the same time, the required single feed distribution rate should be within the range of 8–10 kg; therefore, the feed mixer-distributor ensures feed distribution in accordance with zootechnical requirements.

Experimental studies aimed at substantiating the parameters of the feed mixer-distributor were carried out under farm conditions at Tobylgy Agro Group, Ili District, Almaty Region.

Under farm conditions, there was a need to prepare a feed mixture for fifty cows for three feeding cycles per day.

According to the feeding ration, a feed mixture consisting of 250 kg of silage, 84 kg of hay (alfalfa), and 50 kg of crushed barley was prepared for a single feeding cycle, with a total mass of 384 kg.

During the experimental investigations, the required power consumption was determined using a TRK-50 strain gauge sensor and an ACD-1R-0.5 electronic dynamometer.

In the experimental prototype, the auger rotational speed was regulated by changing the PTO rotational speed of the tractor. During the experiments, the auger rotational speed was 30 min^{-1}. Previous studies showed that, in all similar machines, the rotational speed of the horizontal auger is generally regulated within the range of 24–30 min^{-1}. The rotational speed of the leveling shaft during the experiments was 20 min^{-1}.

After loading the prepared feed mixture components into the hopper of the feed mixer-distributor, a control component consisting of 3 kg of wheat was added. A stopwatch was then started.

To determine the effect of mixing time on mixture uniformity, samples were collected during operation of the feed mixer-distributor. The samples were taken after 2, 4, 6, and 9 min of operation.

To obtain each sample, the discharge gate of the mixer was slightly opened, and a small portion of the feed mass was unloaded. From this unloaded mass, 10 samples weighing 70–80 g each were collected. The samples were taken using a 0.3 L cup.

During the processing of the experimental data, the control component was separated from each sample and its mass was determined.

It should also be noted that the mass of each sample differed during sampling. Therefore, during the processing of the experimental data, the average sample mass was first determined.

For each sample, the reduced mass of the control component corresponding to the average sample mass was then determined as follows:

$$m_{kp} = \frac{m_c \cdot m_{ki}}{m_{oi}}, \tag{11}$$

where m_c – is the average mass of the samples, g, determined using Equation (13);
m_{ki} – is the mass of the control component in the *i*-th sample, g;
m_{oi} – is the mass of the *i*-th sample, g.

$$m_c = \frac{\sum_{ic}^{n} m_{ki}}{n}, \tag{12}$$

The results of processing the experimental data obtained after six minutes of operation of the feed mixer-distributor are presented below (Table 2).

Table 2. Results of processing the experimental data after six minutes of operation of the feed mixer-distributor.

Experiment №	m_{oi}, g	m_{ki}, g	m_{kni}, g	$(m_{kni} - m_c)^2$	$(m_{kni} - m_c)^2$
1	47,2	2,4	2,39	0,06	0,0036
2	45,2	2,2	2,29	0,04	0,0016
3	48,3	2,3	2,24	0,09	0,0081

4	47,2	2,3	2,29	0,04	0,0016
5	49,2	2,4	2,29	0,04	0,0016
6	46,8	2,3	2,31	0,02	0,0004
7	47,2	2,2	2,19	0,14	0,019
8	46,5	2,4	2,43	0,1	0,01
9	46,5	2,5	2,53	0,2	0,04
10	46,3	2,3	2,34	0,01	0,0001
	m_c = 47,04		m_c = 2,33		$\sum$ 0,086

$$\delta = \sqrt{\frac{\sum_{i=1}^{n}(m_{kni} - m_c)^2}{n-1}} = \sqrt{\frac{0{,}086}{9}} = 0{,}0948.$$

The coefficient of variation is determined using the following equation:

$$\upsilon = \frac{G \cdot 100}{m_c} = \frac{0{,}095 \cdot 100}{2{,}33} = 4{,}077 = 4{,}1.$$

Uniformity of the mixing process:

$$\mathrm{O} = 100 - \upsilon = 100 - 4{,}1 = 95{,}9\%.$$

Thus, the experimental prototype of the compact feed mixer-distributor ensures the preparation of total mixed rations with a mixture uniformity of 95.9% for all types and age groups of animals.

After processing the experimental data, the mixture uniformity values corresponding to 2, 4, 6, and 9 min of mixer operation were determined (Figure 8).

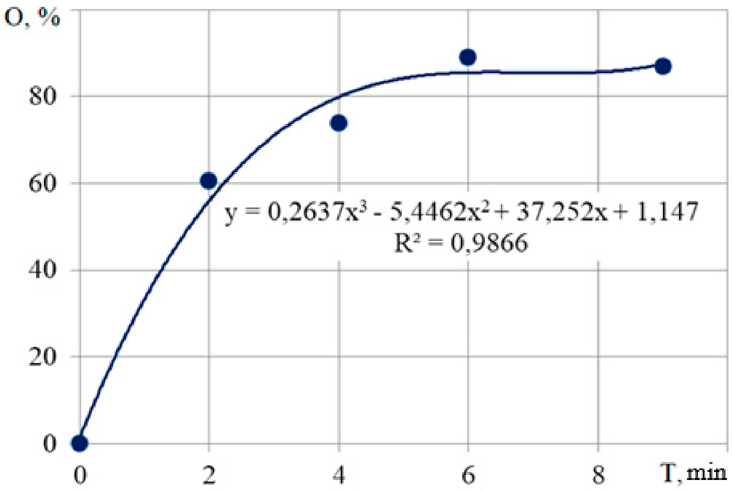

Figure 8. Effect of mixer operating time on the uniformity of mixing of total mixed ration components.

The graph shows that, after 5–6 min of operation, the mixture uniformity reaches 90%, after which the change in uniformity stabilizes at approximately the same level. Therefore, for the proposed feed mixer-distributor, an operating time of 5–6 min can be considered the optimal duration of the mixing process.

In conventional feed mixers, the mixing process occurs by lifting the feed mixture until collapse. In this case, the feed mass collapses in large portions and is subsequently transported toward the center of the hopper. To distribute the smaller components throughout the entire feed mass, the collapse process must be repeated several times.

In the experimental prototype of the feed mixer-distributor, two leveling finger shafts are installed in the upper part of the hopper. During operation of the machine, the finger shafts transport the feed mass toward the end walls of the hopper after a certain lifting height is reached.

In this case, the feed mixture in the central part of the hopper is not lifted to the point of collapse, and a small portion of the mass is immediately transported toward the end walls of the hopper. As a result, accelerated dual-circuit mixing occurs, which reduces the mixing time.

Therefore, the presented graph (Figure 8), showing the change in mixture uniformity depending on machine operating time, represents a characteristic relationship for the feed mixer-distributor equipped with the leveling–mixing device.

This relationship can be expressed by the following equation:

$$O = 0{,}263T^3 - 5{,}4462T^2 + 37{,}252T + 1{,}147, \tag{13}$$

where T is the operating time of the feed mixer-distributor, min.

Differentiating this equation, the rate of change in mixture uniformity υ_o can be obtained as follows:

$$\upsilon_o = \frac{dO}{dT} = (0{,}2637T^3 - 5{,}4762T^2 + 37{,}252T + 1{,}147)' =$$

$$= 0{,}7911T^2 - 10{,}8924T + 37{,}252 \tag{14}$$

To clearly illustrate the rate of change in mixture uniformity depending on the duration of the mixing process of the feed mixer-distributor, a graphical representation of the obtained function is presented in Figure 9.

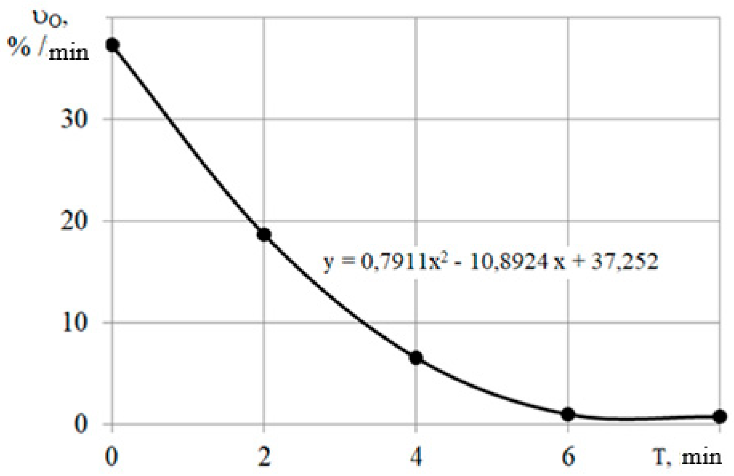

Figure 9. Dependence of the rate of change in mixture uniformity on the duration of the mixing process.

This graph clearly demonstrates that the optimal operating duration for the proposed feed mixer-distributor design is 5–6 min.

According to the technical specifications of modern feed mixers, the mixing time generally ranges from 6.0 to 7.0 min [26]. When the leveling–mixing device is used, the optimal mixing time decreases to 5.0–6.0 min, indicating an acceleration of the mixing process by 15.4%.

The theoretical investigations showed that the rational rotational speed of the finger shaft is $n \geq 19$ min^{-1}, and that feed mixture release from the surface of the fingers of the leveling–mixing shaft should occur at finger rotation angles of 30–38°. The results of the experimental studies demonstrated that, at a finger shaft rotational speed of $n \geq 20$ min^{-1}, smooth movement of the feed mass toward the end walls of the hopper was observed (Figures 10 and 11).

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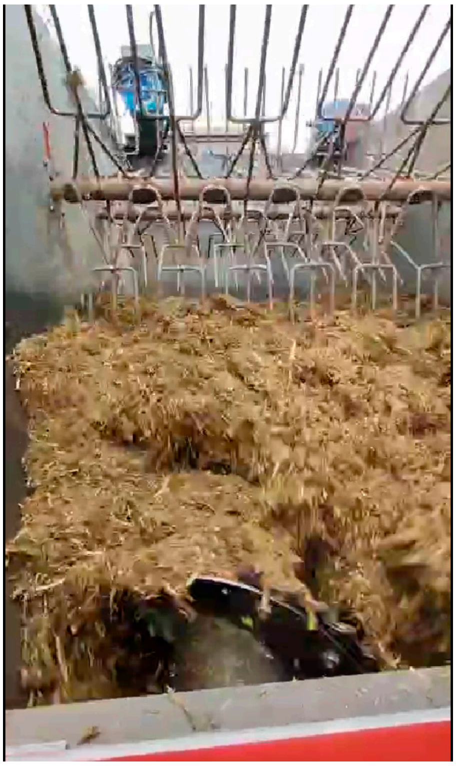

Figure 10. Position of the leveling–mixing finger shaft at the initial stage of feed mass discharge.

Figure 11. Position of the fingers of the leveling–mixing shaft at the final stage of feed mass discharge.

The figures show that, at the initial stage of feed mass discharge, the fingers are positioned vertically, whereas at the final stage of discharge the fingers are inclined at an angle of approximately 30–38°, which confirms the validity of the theoretical investigations. It should also be noted that stable operation of the finger shaft was observed during the experiments, i.e., the feed mixture slid from the finger surface smoothly and without scattering.

Thus, these results confirm the validity of the presented investigations and the rationality of the kinematic modes of the finger shaft determined through theoretical analysis.

5.3.2. Energy Evaluation of the Leveling–Mixing Device

For the energy evaluation, it was necessary to determine the power consumption values during operation of the feed mixer-distributor both with and without the leveling device. Therefore, two experiments were conducted.

In the first experiment, a feed mixture with a specified mass was loaded into the feed mixer-distributor, and the power consumption during operation with the leveling device was determined.

In the second experiment, the same loaded feed mass was used to determine the power consumption of the mixing process without the leveling device.

To conduct the above-mentioned experiments, a TRK-0.5 strain gauge sensor was installed on the shaft of the main gearbox and connected through an ACD-1R-0.5 electronic dynamometer (Figure 12).

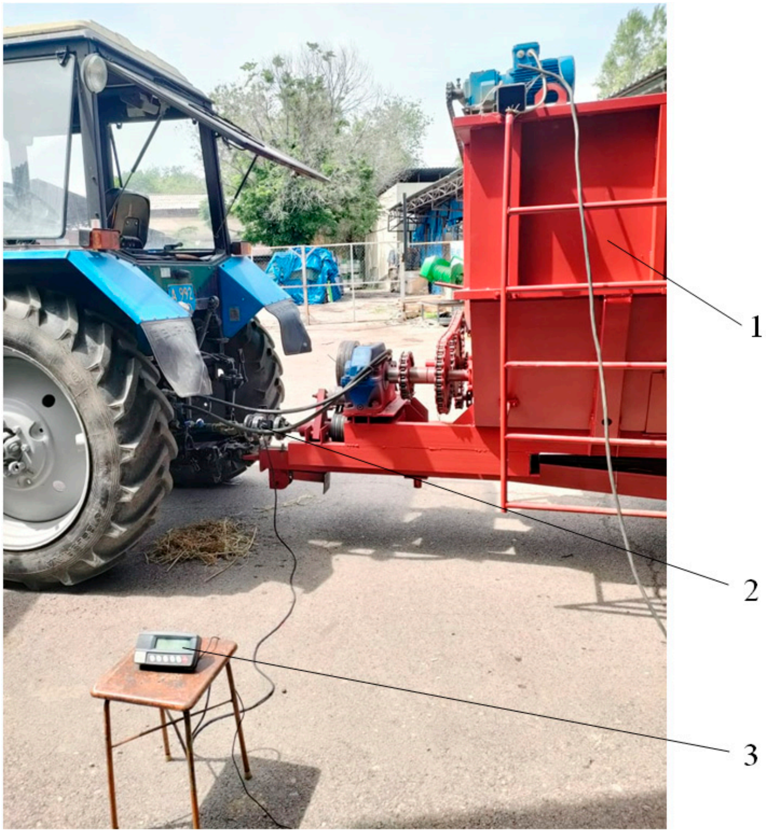

Figure 12. General view of the feed mixer-distributor with connected measuring instruments. 1 – feed mixer-distributor; 2 – strain gauge sensor; 3 – electronic dynamometer.

For the experiments, a feed mixture corresponding to a single feeding cycle for 50 cows was prepared. Considering that the average daily ration per cow under three feeding cycles consists of 15 kg of silage, 5 kg of hay, and 3 kg of compound feed or grain feed, the following quantities were loaded into the hopper of the feed mixer-distributor for one feeding cycle: (15/3) × 50 = 250 kg of silage; (5/3) × 50 = 84 kg of hay; and (3/3) × 50 = 50 kg of crushed barley. The total feed mixture mass was 384 kg.

During the experiments, the strain gauge sensor was installed on the shaft of the main gearbox, while its shaft was connected to the tractor power take-off (PTO) shaft through a cardan shaft.

Under operating conditions, the tractor PTO rotational speed was 450 min^{-1}, the auger rotational speed was 30 min^{-1}, and the rotational speed of the leveling–mixing finger shaft was 20 min^{-1}.

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Initially, the operation of the feed mixer-distributor under idle conditions was checked. The rotational speeds of the auger and the leveling shaft corresponded to the above-mentioned operating conditions, and the resistance torque values of the machine working bodies were determined.

The average resistance torque during idle operation of the feed mixer-distributor was M_c= 8,3 N·m.In this case, the power consumption during idle operation is determined using the following equation:

$$N_{io} = M_c \cdot \omega = M_c \cdot \frac{\pi \cdot n}{30} = 8{,}3 \cdot \frac{3{,}14 \cdot 450}{30} = 397 \approx 0{,}4kW.$$

Next, all feed mixture components were loaded into the hopper, and the mixing process was carried out for six minutes under full loading conditions. The operating process of the feed mixer-distributor equipped with the leveling–mixing device was recorded using a smartphone. After that, partial unloading of the feed mixture was performed, the tractor PTO was disengaged, and the drive of the leveling–mixing shaft was disconnected. The feed mixture was then reloaded to full capacity, and the operation of the feed mixer-distributor without the leveling–mixing shaft was recorded.

Processing of the experimental data showed that the average resistance torque during operation with the leveling–mixing device wasM_{pc}= 71,5 N·m (Figure 13).

Consequently, the power consumption of the machine equipped with the leveling–mixing device was N_p = 3,37 kW.

Figure 13. Instantaneous values of the resistance torque during operation of the machine equipped with the leveling–mixing device.

Processing of the operating data obtained for the machine without the leveling–mixing device showed that the average resistance torque was 96 N·m (Figure 14). In this case, the power consumption was N_{md} = 4,52 kW.

Figure 14. Instantaneous values of the resistance torque on the main gearbox shaft.

These data show that operation of the feed mixer-distributor without the leveling–mixing device results in a 34% increase in power consumption compared with operation of the feed mixer-distributor equipped with the leveling–mixing device.

Observation of the machine operating without the leveling–mixing device showed that the feed mass was lifted to a certain height and remained in this position until collapse occurred. This indicates that the collapse process takes place after complete loading of the machine, which additionally contributes to increased energy consumption and longer mixing duration.

Thus, the results of these experiments confirm that equipping the feed mixer-distributor with a leveling–mixing device reduces the energy consumption and accelerates the mixing process, thereby validating the proposed hypothesis.

As a result of the theoretical and experimental investigations, a new technology for the feed mixing process was proposed, a structural and technological scheme of a feed mixer-distributor equipped with a leveling–mixing device was developed, and the kinematic operating modes of the machine were substantiated. The conducted studies confirmed the validity of both the proposed hypothesis and the theoretical investigations.

6. Discussion

Analysis of existing feed mixer-distributor designs showed that the mixing process in such machines is carried out by lifting the feed mass until collapse occurs. In this process, the lifted feed mixture collapses in large portions and is transported by the horizontal auger toward the center of the hopper, where the feed mass is again lifted until collapse. As a result, the duration of the mixing process required to achieve the target mixture uniformity increases, while the energy consumption associated with lifting the feed mass also rises.

The developed feed mixer-distributor is equipped with a new leveling–mixing device. In this machine, the horizontal auger collects the feed mass in the center of the hopper, and after a certain lifting height is reached, the fingers of the leveling–mixing device direct the feed mixture toward the end walls of the hopper. This dual-circuit mixing process occurs during each rotation of the finger shaft, thereby accelerating the mixing process. Consequently, the developed feed mixer-distributor differs from existing machines both in design and in the operating principle of the mixing process.

Within the framework of this study, analytical expressions were obtained for determining the rational rotational speed of the leveling–mixing finger shaft and the velocity of feed mass movement toward the end walls of the hopper. This represents the scientific novelty and theoretical contribution of the proposed process.

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Unlike the mixer designs considered in [27,30,32], where the improvement of the mixing process is mainly achieved by changing the geometry of the main working bodies or by optimizing the loading and mixing parameters, the proposed design introduces an additional leveling–mixing device that changes the internal circulation pattern of the feed mass. This device prevents the feed mixture from being lifted to the point of uncontrolled collapse and instead provides controlled dual-circuit redistribution toward the end walls of the hopper.

Laboratory experiments conducted to validate the theoretically determined kinematic modes of the leveling–mixing finger shaft demonstrated that the feed mixture movement process occurred without feed scattering and with timely release of the feed mass from the finger surface. These results confirm the validity of the theoretical investigations, while the rationality of the determined kinematic modes is supported by the experimental results demonstrating accelerated mixing performance.

It should also be noted that the comparative experiments conducted with and without the leveling device demonstrated the effectiveness of the leveling–mixing device itself. Incorporating this device into the mixer design reduces the energy consumption and accelerates the mixing process.

This result is consistent with the conclusions of Li et al. [31], who showed that the energy intensity of horizontal TMR mixers strongly depends on the interaction between fibrous material and the working bodies. In the present study, the reduction in power consumption was achieved not only by selecting a rational operating mode but also by changing the trajectory of feed mass movement inside the hopper.

It is expected that the efficiency of the proposed device may increase with increasing hopper capacity of the feed mixer-distributor.

One limitation in applying the obtained analytical expressions to other feed materials may be the need to refine the friction coefficient depending on the type of material and its moisture content.

A possible continuation of the present research is the integration of the leveling–mixing device into existing feed mixer-distributor designs. Another promising direction is the application of the obtained analytical expressions for substantiating the kinematic modes of similar leveling, distributing, and mixing devices.

7. Conclusions

1. To accelerate the mixing process, a hypothesis was proposed stating that continuous dual-circuit mixing can be achieved by equipping the feed mixer-distributor with two leveling–mixing finger shafts, which, after a certain lifting height of the collected feed mass is reached, divide it into two flows directed toward the end walls of the hopper. In this case, continuous dual-circuit mixing is performed during each rotation of the leveling–mixing shaft.

A structural and technological scheme and engineering documentation were developed, and an experimental prototype of the feed mixer-distributor was manufactured. The machine consists of a 3.0 m^3 hopper, two horizontal augers, two leveling–mixing finger shafts, a loading conveyor, and a drive mechanism.

2. Theoretical investigations were carried out, and analytical expressions were obtained for determining the circumferential velocity of the fingers of the leveling–mixing device, which should ensure movement of the feed mixture without scattering and provide timely release of the feed mass from the finger surface at a finger rotation angle of 30°. Calculations based on the obtained analytical expressions showed that the critical circumferential velocity of the fingers was 0.8 m/s, while the rotational speed of the finger shaft was 19 min^{-1}.

An analytical expression was also obtained for determining the velocity of feed mixture movement along the finger surface. Based on the calculations, the optimal value of this velocity was determined to be 0.7 m/s. This value corresponds to the rational velocity of feed mixture movement toward the end walls of the hopper.

3. Laboratory experiments of the feed mixer-distributor were conducted at a rotational speed of the leveling–mixing finger shaft of $n = 20$ min^{-1}. Under this kinematic mode, the fingers transported

the feed mass without scattering, while timely release of the feed mass from the finger surface was ensured at a finger rotation angle of $\alpha = 30°$.

Special experimental studies showed that the optimal mixing time required to achieve the target mixture uniformity was 5.5 min. This value is 15.4% lower than the operating time of existing machines.

Comparative experiments also showed that incorporating the leveling–mixing device into the feed mixer-distributor design reduced the power consumption of the mixing process by 34%.

All the above results confirm the validity of the selected structural and technological scheme of the machine, as well as the theoretical investigations aimed at determining the kinematic modes of the leveling–mixing device.

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