Conference Paper

Experimental and Theoretical Substantiation of Device Performance in Soy Milk Production for Animal Feed

G G Klasner, V Yu Frolov, and V F Kremyanskiy

Department Animal husbandry mechanization and life safety, Kuban State Agrarian University named after I.T. Trubilin, Krasnodar, Russia

Corresponding Author:
G G Klasner
egor.klasner.91@mail.ru

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Abstract

The article presents a device to obtain soybean milk, Tofu soybean curd, a soy protein base for feed preparation for farm animals and poultry as a product of soybean grain processing. The device combines a number of technological operations, such as grinding the grain of legumes to obtain fine grinding, the extraction of soy protein into the emulsion and the separation of the protein emulsion into two homogeneous fractions: a liquid protein base (soy milk) and undissolved residue -- Okara. The kinematics of the movement of soybean grain in a soaked form over the abrasive surface of a cone with curved grooves applied is considered, a final formula for the speed of movement of the grain is obtained. The volumetric and mass productivity of the grain chopper is determined theoretically and experimentally depending on the main factors affecting the process.

Keywords: soaked soybean grain, kinematics of the movement of soybean grain in the soaked form, abrasive surface of the cone, soy milk, high-protein feed.

1. Introduction

The deficiency of protein in the diet of animals creates a tendency to reduce the profitability of agricultural enterprises due to the lack of productivity of animals and birds [2, 3].

Based on the analysis of the nutritional value of feed, we can conclude that soybean grain can solve the problem of protein deficiency in the diet of animals. Soy is the main supplier of vegetable protein. It contains 17.3 % fat, 26.5 % carbohydrates and 34.9 % protein, as well as the most important amino acid composition and content, while the feed value reaches 1.45 feed units. Soybean is a common agricultural crop and is used both in its pure form after appropriate processing, and in compound feeds for almost all types of farm animals. The main value of soybean grain in comparison with other feed crops lies in the low cost of protein, which in its composition is an excellent analogue of expensive animal protein.

Scientists agree that the most promising direction in the preparation of soybeans to feed farm animals is the preparation of a liquid protein suspension, that is, soy milk, which is not inferior in its biological value to whole, cow's milk.

However, the use of soybean grain in diets to feed farm animals in the management of private farms or a small livestock farm is not large, due to the lack of universal small-sized and low-energy equipment for processing grain for animal feed.

Thus, there is a need to develop a universal technology for protein emulsion production, which is applicable in the conditions of conducting personal subsidiary farming.

2. Methods and Materials

Based on the implemented patent search, as well as the analysis of methods and technologies involving the use of commercially available equipment for the preparation of soy milk from soybean grain, a universal device was developed (patent for invention of the Russian Federation No. 2614777, No. 2621274, patent for useful model of the Russian Federation No. 161559, No. 163069) [13, 14] to process soybean grain for animal feed. A distinctive peculiarity of the proposed method to process soybean grain, implemented by the device being developed (Figure 1), is the integration of a number of technological operations associated with the grinding of grain material, followed by mixing with water to extract the protein into an emulsion, separation into milk and Okara in one process [8].

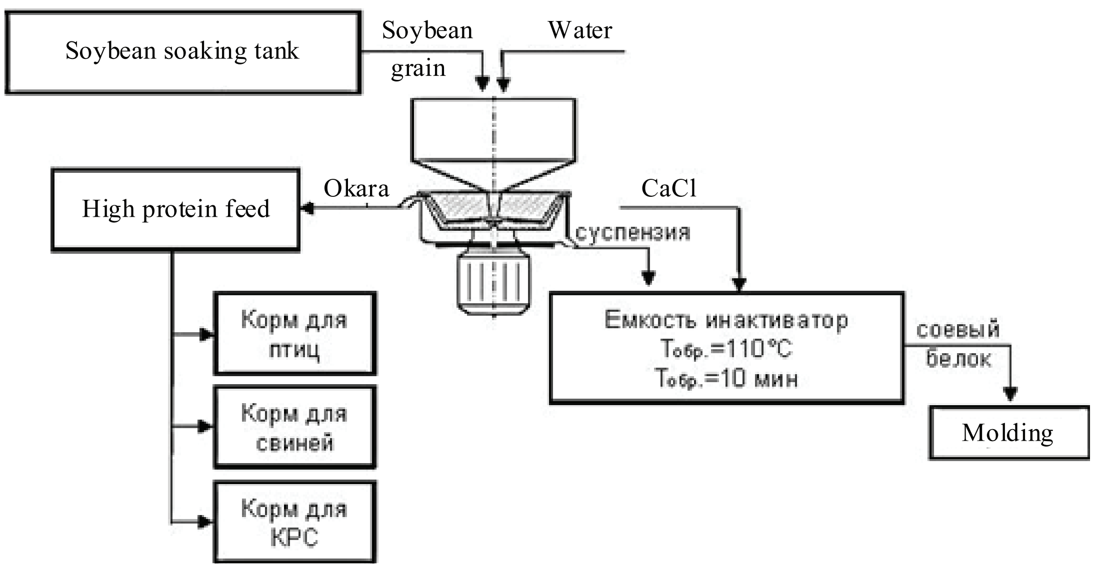

Figure 1: Waste-free technology for protein feed.

The technology of soy protein production [8] is as follows. Soybeans need to be soaked in water at room temperature for twelve hours. Then the grain collected in itself is fed into the grinding chamber simultaneously with the water flow in the ratio of 1:10. The soy milk obtained is separated by sieve from the undissolved residue. Further, after appropriate heat treatment, soybean milk can be given to feed animals or cook tofu curd by coagulating the protein with a solution $CaCl_2$, dividing the protein suspension into serum and soy protein (Fig. 1) [7].

The main element of the proposed technology for high-protein feed based on soybean grain is a soybean grain chopper.

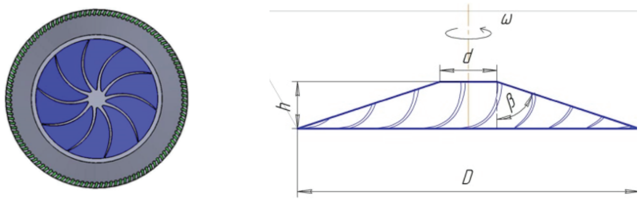

Figure 2: General view. Driving abrasive disk with curved grooves.

In the proposed device, the main technological operation is the abrasion of the soaked soybean grain to a fine state by means of a truncated cone with curvilinear grooves and an applied abrasive over its entire surface (Fig. 2).

During operation of the chopper, soybean grains are located on a conical abrasive surface, that is, they have two degrees of freedom, which grain position can be described by two generalized coordinates, which are conveniently the radial coordinate r -- the distance from the top of the cone to the current position of the grain along the generatrix of the cone, and angular variable θ representing the angle of rotation of the radius -- the vector of soybean grain as it moves along the surface of the cone. To simplify the calculation, we neglect the dimensions of the upper horizontal platform, that is, we assume that the cone is not truncated.

In the reference system associated with a rotating cone, the equation of motion is [1, 4]:

$$r = r_0 ch((bt) -- 1); \quad (1)$$

$$\varphi = \frac{q^2 t^2}{2}; \quad (2)$$

It should be noted that in a fixed reference system the angle of rotation of the grain is equal to:

$$\theta = \omega t - \varphi;$$

that is, the angles θ and φ counting in different directions.

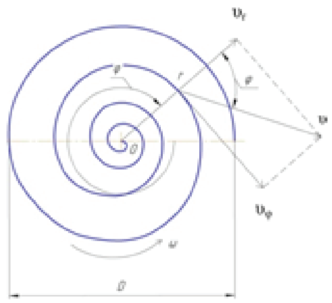

Figure 3: The trajectory of the grain in reference system associated with rotating cone (*D* -- diameter of the cone at the bottom base; *r* -- distance of grain along forming a cone from Oa_1 its rotation; υ_r, υ_φ -- radial and azimuthal velocity components υ; ψ -- gap between the velocity vector υ and forming *r*).

From equality (1) and (2) we find the equation of the trajectory of the grain:

$$r = r_0(ch(\frac{b}{a}\sqrt{2\varphi}) - 1); \tag{3}$$

Graph of the trajectory of the grain, when $\frac{b}{a} = \frac{1}{\sqrt{2}}$ (as $f,\ sin\beta,\ cos\beta$ is less than 1, they can be neglected when qualitatively considering the movement of the grain) (Figure 3).

For a given time direction, the angle is counted clockwise.

As r increases, the velocity υ_r grows approximately linear law $\upsilon_r = br$, thus, addendum $\frac{gfrsin\beta}{2\upsilon_r}$ remains approximately constant with increasing r, and the remaining terms increase according to the proportional law. Therefore, with the degree of accuracy that was adopted in the previous article [5, 6]: you can write:

$$\upsilon_\varphi = \omega r - \frac{r^2}{2\upsilon_r}(q^2 + f\omega^2 sin\beta cos\beta); \tag{4}$$

Equation (4) is valid in the fixed frame, as indicated by the term ωr on the right-hand side of equality (4). Considering that f < 1, the term $f\omega^2 sin\beta cos\beta$ can be neglected compared to q^2, the equation for υ_φ in the portable reference system, rotating with the cone has the form [3]:

$$\upsilon_\varphi = -\frac{r^2q^2}{2\upsilon_r} = -\frac{r^2q^2}{2\sqrt{b^2r^2 + 2ar}}; \tag{5}$$

The mark «--» in this equation indicates the direction of reference of the angle φ, which was noted above.

The volumetric productivity of the grinder of soybean grain Q [3] is determined by the geometry of the plant and the radial component of the velocity of the grain, the same in both the fixed and moving reference systems.

$$Q = \pi DZ\upsilon_r = \pi DZ\sqrt{b^2r^2 + 2ar}; \tag{6}$$

where Z -- the grain size between the conical surface and the device cover.

The mass productivity of the grinder of soybean grain Q is defined as [4]:

$$G = p{\cdot}Q; \tag{7}$$

where p soybean grain density, kg/ m^3;

Q Volumetric performance m^3/h.

Formula (6) is valid when there are no guide grooves on the performance of the device on the surface of the abrasive cone. Figure 2 shows a part of the grooves inclined at an angle *α* to the radial direction.

We first consider the case at an angle ψ greater than the inclination angle of the grooves a.

Then the angle between the velocity vector of the falling grain and the groove is ψ = α. In the case of elastic collision, the speed of the grain does not change, and the angle of incidence equals the angle of reflection. Therefore, the angle between the radial direction and the direction of the velocity of the reflecting grooves is. α -- (ψ -- α) = 2α -- ψ. Therefore, after the grain is reflected from the grooves, the radial component of its velocity is equal to:

$$\upsilon_r' = \upsilon' cos(2\alpha - \psi) = \upsilon cos(2\alpha - \psi); \tag{8}$$

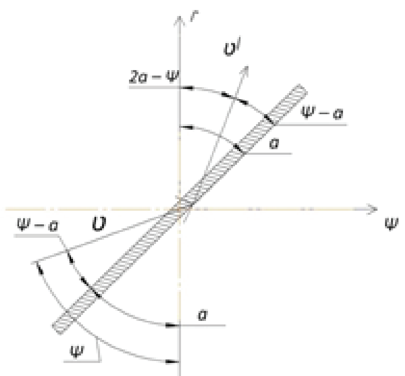

Figure 4: the scheme of collision of grain with grooves (hatched) at angle ψ > α; υ_1 υ' is the speed of the grain after the collision with the groove.

The speed υ_r^1 reaches its maximum when α = $\frac{\psi}{2}$. In this scheme, after reflection the grain moves along the radius of the azimuthal velocity component is absent. Thus, when the incline of the grooves α = $\frac{\psi}{2}$, then maximum performance is achieved.

When a = ψ; υ_r' = υ_r, and the grains run parallel to the grooves. There is a minimal effect on the movement of the grain. The performance of the device will be the same as in the absence of blades.

When the inclination angle of the grooves α is greater than ψ, the grain hits the blades from the inside. In this case, formula (8) remains valid, however, with increasing angle α

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from ψ to $\frac{\psi}{2}$ + 45^0 device performance decreases from the value given by formula (8) to zero, and at an angle α > $\frac{\psi}{2}$ + 45^0, the grain does not go out of the device: the grooves do not allow them to go outside.

Thus, there is an optimum from the point of view of the maximum performance of the device when inclining the grooves α = $\frac{\psi}{2}$, as well as the critical angle of inclination α = ψ, in which the grooves do not influence the movement of the grain.

The tilt angle more than is not profitable, because the performance is sharply reduced, and when α = $\frac{\psi}{2}$ + 45^0 the output of the crushed grain from the device is missing.

The above conclusion about the impact of grooves location on the device performance is approximate in nature associated with a simplified model of grain movement.

Nevertheless, the conclusion about the existence of an optimal angle at which productivity drops to zero is confirmed in practical studies of the developed soaked soybean shredder.

Taking into account the requirements for technological lines for the preparation of soy milk, the main purpose of the experimental studies was to confirm the theoretically obtained dependencies

Experimental studies have studied the effect of the design-mode parameters of the shredded soybean shredder on its performance.

A prototype was made (Figure 5), on the basis of which a number of multifactor experiments were conducted in order to experimentally substantiate the design-mode parameters of the shredder.

Figure 5: General view of grain grinder in asoaked form with interchangeable abrasive discs.

To measure the energy characteristics of the device we used K-505. Laboratory flasks and VLTK-500 electronic balance were used to measure the quantitative protein yield. To change the motor speed, a rheostat built into the experimental setup was used. The temperature of the extractant was measured with a mercury thermometer with a scale up to 130 °C. The gap between the abrasive discs was measured with a caliper. The volume of the obtained extractant was measured with a beaker with a scale [8, 9].

The main optimization criteria for abrasion process of soaked soybean grain were selected: protein yield to the extractant *(G),* shredder productivity *(Q)* and energy consumption per process *(N).* The factors influencing the technological process are

(Table 1): the size of the gap between the grinding wheels coated with abrasive (h); roughness (Ra); rotational speed (ω) of the lower disk; the angle of curvature (α) of the guide grooves [10].

TABLE 1: Factors and levels of their variation.

Level	Factors			
	Angular velocity of rotation of the lower disk ω, rad / s	Abrasive grain size R_a, mkm	Groove direction angle α	Gap between the discs h, mm
	X_1	X_2	X_3	X_4
Upper (+1)	172	50	α-120°	5
Main (0)	169	250	α-90°	4
Lower (--1)	141	450	α-60°	3

The factors presented in Table 1 meet the requirements of uniqueness, independence, controllability and operationality. Uncontrollable, but controlled factors -- air temperature and humidity, atmospheric pressure were taken into account at the beginning of the experiment.

3. Results

Experimental studies were based on the works of scientists S.V. Melnikov, N.V. Asanova, Yu.B. Kurkova, V.V. Kirsanova, V.R. Aleshkina and other authors.

Kiefer's optimal plan was used to conduct research, which included fifteen results of the experiment on the Plakett-Berman matrix and finding the criteria for process optimizing, carried out processing and constructed mathematical models. So for abrasion process of grain in a soaked form, the criteria for optimizing the process were obtained: the yield of protein in extractant is G (Y1 response), the performance of the proposed device (Q) and the energy consumption per process N kW (Y2 response). According to the experimental data obtained, rational values were determined [11, 12].

To confirm the assessment of factors influence on the process, second-order regression equations (Statistica v. 5.5 from StatSoft (USA)) were obtained using the experimental data, which look like this:

$$Y_1 = 0.36357 - 0.00147X_1 - 0.00497X_2 - 0.0858X_3 - 0.0658X_4 + 0.000021X_2X_3 + 0.0000135{X_1}^2 + 0.0000348{X_2}^2 + 0.00083{X_3}^2 + 0.00063{X_4}^2$$

$$N_1 = 1.5581 - 0.00019\omega - 0.00011R_a - 0.1076\alpha_3 - 0.10863h - 0.00001\omega h + 0.00001R_a\alpha + 0.0006\alpha h + 0.00897\alpha^2 + 0.013897h^2$$

$$Y_2 = 10.27083 - 1.99227X_1 + 2.36817X_2 - 2.29653X_3 - 5.04557X_4 + 0.00005X_1X_2 - 0.0002X_1X_3 + 0.0004X_1X_4 + 0.0002X_2X_3 + 0.0002X_2X_4 + 0.0003X_3X_4 + 0.019X_1^2 - 0.0229X_2^2 + 0.02223X_3^2 + 0.04897X_4^2$$

$$T_2 = 70.5946 - 0.00513\omega + 0.0343R_a - 10.01193\alpha - 21.30593h + 0.0008\omega h + 0.0031R_a h + 0.0134\alpha h - 0.0001R_a^2 + 1.0943\alpha^2 + 1.96527h^2$$

$$Y_3 = 21.35202 + 3.9244X_1 + 5.452133X_2 + 4.831567X_3 - 5.29423X_4 + 0.0009X_1X_2 + 0.0005X_1X_3 - 0.000086X_1X_4 + 0.0015X_2X_3 - 0.0007X_2X_4 + 0.000089X_3X_4 - 0.0379X_1^2 - 0.05217X_2^2 - 0.04760X_3^2 + 0.0514X_4^2$$

$$g = -83.4565 + 0.0236\omega + 0.017367R_a - 8.61847\alpha - 3.9973h + 0.000006\omega R_a - 0.000032\omega\alpha - 0.001\omega h + 0.0007R_a\alpha - 0.016R_a h - 0.0261\alpha h - 0.00007R_a^2 + 1.0806\alpha^2 + 1.11143h^2$$

After finding mathematical models, the optimum coordinates were obtained and the response surfaces of the impact of the design-mode parameters of the shredder on productivity were constructed.

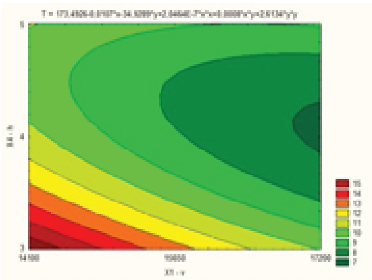

Figure 6: Cross-sectional surface performance on the plane X_1(ω) from X_4(h).

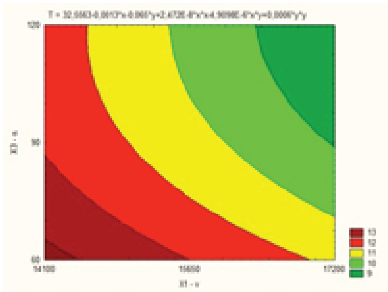

Figure 7: Cross-sectional surface performance on the plane X_1(ω) from X_3(α).

The dependency analysis in Figure 6 shows that an increase in the rotational speed (ω) of an abrasive disk, as well as an increase in the gap (h) between the disks, affects the reduction in the time (t) spent on the process. So the time (t) spent on the process is minimal and equal to t = 7 seconds at the speed of rotation of the abrasive disk ω = 168... 172 rad/s with a gap between the disks h = 3.9...4.2 mm

Based on the analysis of the dependences presented in Figure 7, we can conclude that with an increase in the angle of curvature of the groove (α), the time (*t*) spent on the process decreases. This is explained by the fact that grooves with an angle of inclination greater than 90° act as guide grooves, the direction of which coincides with the course of rotation of the disk, which in turn contributes to the accelerated descent of grain into the separation zone. In this regard, the time optimal angle of curvature of the groove should be within α = 90°...120°.

Figure 8 shows the dependence of the time spent on the process on the rotation speed (ω) and the value of the applied roughness (Ra) on the lower abrasive disk, based on the analysis of which it can be argued that with the rotation frequency of the lower abrasive disk ω = 170... 172 rad/s with an abrasive roughness of Ra = 440...450 μm, the time spent on the process is t = 8 s.

After analyzing the dependence presented in Figure 9, we can conclude that with an increase in the rotational speed of the lower abrasive disc IDZ from n = 1300 min^{-1} to 1700 min^{-1}, the productivity increases from 0.1 to 0.25 kg/s, respectively.

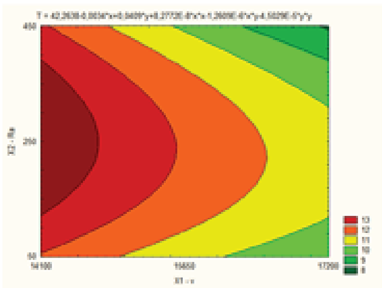

Figure 8: Cross-sectional surface performance on the plane X_1(ω) from X_2(Ra).

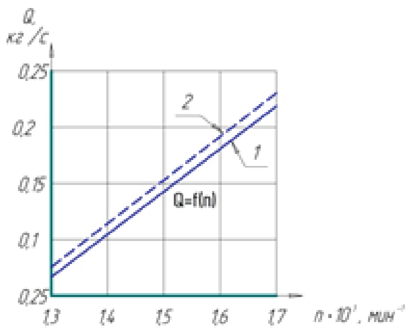

Figure 9: Dependence of the rotational speed of the lower disk on the chopper performance 1 -- experimental 2 -- theoretical.

The discrepancy between the data obtained by theoretical and experimental studies does not exceed 5 %.

4. Conclusion

In the process of research, it was established that the rotation speed (ω) and roughness (R_a) of the abrasive disk, as well as the gap (h) between the disks, have the most significant effect on the protein extraction process.

As a result of theoretical studies, the following results were obtained: the main design-mode parameters of a soaked soybean shredder; the equation of grain movement along the surface of curvilinear grooves of a truncated cone; volume and mass performance formulas.

As a result of experimental studies, rational parameters of the grain grinding process in a soaked form were determined, followed by protein extraction, so with a rotation frequency ω = 170...172 rad/s, with an abrasive grain size R_a = 440...450 microns, with a gap between the disks h = 3.9...4.2 mm and at the angle of curvature of the groove within α = 90°...120°, the optimum time spent on the process t = 7...8 s is reached.

To confirm the theoretical premises, experimental studies of the effect of the rotational speed of the movable disk (n) on performance (Q) were carried out, while the discrepancy between the data obtained by theoretical and experimental studies does not exceed 5 %.

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