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Effect of Rotational Speed and Gap between Rotating Knives of the Grinder on the Yield Stress and Water-Binding Capacity of Fine Ground Chicken Bone

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Abstract: This article presents the results of the study of the dependence of yield stress (YS) and water-binding capacity (WBC) on mechanical processing of meat and bone raw materials when changing the rotational speed and the gap between the rotary knives of the grinder. It is revealed that the parameters of YS and WBC also increase when the rotational speed increases. Thus, the highest values of YS (943.29 Pa) and WBC (66.98%) are observed when the rotary knives’ rotational speed is 4000 min⁻¹ and the clearance between knives is 0.16 mm, while the lowest values of YS (635.87 Pa) and WBC (63.83%) are observed when the knives’ rotational speed is 1000 min⁻¹ and the clearance is 0.38 mm. The power consumption of the electric motor of the unit increases as the rotation speed of the working bodies increases and the gap between the knives decreases.

Keywords: chicken bone; grinder; yield stress; water-binding capacity; power; rotation speed; rotary knives

1. Introduction

As a result of the activities of any poultry processing plant, a large number of by-products are inevitably generated. By-products are the products classified as unsuitable for further use within the existing technology [1,2]. In the processing of poultry, almost 20–25% of the live weight of poultry are called “secondary products” of poultry processing (necks, carcasses, wing tips, backs, legs, breasts, etc.), as well as meat and bone residues (MBR) of poultry, which have a significant weight among the by-products of poultry processing [3,4].

Poultry processing produces by-products, such as chicken bones. Most of them cannot be used and are considered as waste, although some parts are used as animal feed. The most promising direction of poultry meat and bone residue processing is the process of fine grinding and the development of technology for obtaining a food additive for meat products. For the processing of meat and bone raw materials, raw materials undergo several stages of grinding. Firstly, they are ground on power grinders, crushers, and then on fine grinders and colloid mills. The required size of the grinding process is achieved by different methods on special machines of different design [5,6].

During fine grinding, the cutting process is carried out at high speeds of cutting elements, followed by high heat release, change of water-binding ability and structural-mechanical properties of the product. These factors make it important to properly determine and calculate the optimal duration of grinding. The degree of grinding of meat determines the depth of technological processing and affects the form of moisture bonds, changing the structural and mechanical characteristics [7,8].
The quality of final products is affected by the type of grinding machine (cutter, cutter-mixer, colloid mills, etc.) during fine grinding. Even though the processes in all machines run similarly, the rational or optimal duration of grinding is different and depends on the kinematic and geometrical characteristics of the machines [9]. The main goal of the fine grinding process is to obtain a homogeneous structure with a given degree of grinding of sausage minced meat [9,10].

As a result of any mechanical action (grinding, stirring, rubbing, cutting, etc.) on the product, the physical properties and technological parameters of the product are changed. To obtain the desired particle size during grinding, a certain amount of useful energy must be applied to the product, which causes a change in product quality. Another part of the total energy is spent to overcome the forces of resistance and friction, which are turned into heat [11–13].

The purpose of this work is to study the effect of mechanical processing of poultry meat–bone residue on the yield stress and water-binding capacity of minced meat–bone residue when changing the rotation speed of rotary knives and the gap of the cutting mechanism of the grinder. The scientific novelty is to determine the rational regimes of the process of bone fine grinding by rotary knives, which allow stabilization of the structural–mechanical characteristics and technological parameters of the meat–bone paste.

2. Materials and Methods
2.1. The Equipment Designation

The grinder is used for fine grinding of meat and meat–bone mass, which is required in the manufacture of frankfurters, wiener, and other sausage products. The grinder is used both in food production lines and independently in preproduction catering enterprises (culinary products and semi-finished products), restaurants, and dietary and children's canteens. The equipment provides high dispersity and homogeneity of raw materials, regulation of grinding rate, and continuous work on grinding of food raw materials (Table 1).

| Machine Capacity (kg/h) | 367 |
|-------------------------|-----|
| Electric motor for knife operation |
| Power (kW) | 3 |
| Rotation speed (rpm) | 2840 |
| Electric motor for screw feeder drive |
| Power (kW) | 0.35 |
| Rotation speed (rpm) | 750 |
| Dimensions (mm) |
| Length | 990 |
| Width | 1390 |
| Height | 350 |

In this study, we used chicken bones after trimming from meat (neck bones, wing bones). Chicken bones were purchased from meat processing enterprises and large meat trading pavilions in Semey city (Eastern Kazakhstan region, Kazakhstan Republic). Before conducting the experiments, the chicken bones were chopped through a 5 mm plate and stored in freezers at a temperature between $-18$ and $-20$ $^\circ$C.

2.2. Design and Operation of the Grinder

The colloid mill is a rotary grinder with a set of movable and fixed knives. The degree of size reduction varies with the gap between the knives and allows particle sizes up to 0.1 mm to be obtained. The grinder includes a screw feeder, filling neck, housing of the
The housing of the set of knives is the cutting body, inside which the raw material is grinded and discharged through the discharge channel and the outlet spout into the receiving container. In the upper part of the set of knives there is a thread for mounting a threaded ring. A ruler with a scale from 0 to 1 mm, with a division value of 0.055 mm, is installed on the body of the knife head, which allows the gap between the movable and stationary ring-shaped toothed knives to be changed according to this scale when turning the threaded ring.

The cutting mechanism consists of five movable and five stationary knives with an angle of sharpening of the end surfaces of 45°, with teeth positioned at an angle of 70° in relation to the axis of rotation (Figures 2 and 3).
A ruler with a scale from 0 to 1 mm, with a scale value of 0.055 mm, is mounted on the housing of the knife head. This allows the clearance between the movable and stationary ring-shaped toothed knives to be changed according to this scale when turning the threaded ring.

The rotor is shaft 4, which transmits the rotation to a set of movable ring-shaped toothed knives 1 and the discharging impeller 3, which are located in the housing of the knife head (Figure 3).

The set of movable ring-shaped toothed knives and the discharging impeller are clamped to the rotor shaft end by the nut 5 (Figure 3). The other end of the rotor shaft is connected to the electric motor through a coupling.

The threaded ring includes a filler neck, a stationary knife, and an arrow ring.

The filler neck is a cylinder with a flange and locking nut at the top and a flange at the bottom for mounting the filler neck to the threaded ring.

The product is loaded into the hopper and transported by a screw into the discharge tube. From here, the food raw material is forced by centrifugal force into the space between
the moving and the paired stationary knife, precisely into the spaces between the teeth. The ground product is thrown into the discharge channel with the help of the discharging impeller.

2.3. Grinding of Chicken Bones with Meat Residue

Chicken bones after deboning of thighs, breasts, wings, and chicken necks were used as meat and bones. The bones were preliminarily crushed on a power grinder to a size of 5 mm.

Fine grinding (up to 50–100 microns) of preliminary crushed meat–bone was carried out on a rotary grinder with a screw feeder. Next, the crushed bones with meat residue was cooled to a temperature of 0 °C. Ice water was added to the frozen minced meat in a 1:1 ratio; then, the mass was mixed and chopped on a rotary grinder. Fine grinding was carried out at different rotational speeds of the movable disk knife from 1000 rpm to 4000 rpm. The gaps between the knives varied between 50 and 380 microns.

2.4. Determination of Yield Stress

To determine the yield stress, we used a texture analyzer ST-1 (company “Radius”, Moscow, Russia), a tapered indenter with an angle of 60°, and a special container for the product (Figure 4). The cone indentor for sausage forcemeat is 45–60 mm long with a cone vertex angle of $2\alpha = 60°$, made of aluminum or other material which is non-hazardous for food products according to the standard GOST R 50814-95 “Meat products”. Methods of penetration were determined by means of the cone and the needle indentor. On each sample, the yield stress was determined in three different points at a temperature of 25 ± 2 °C [14].

![Penetration scheme.](image)

The yield stress $\theta_0$ (in Pa) was determined by the depth of cone immersion and calculated by the formula

$$\theta_0 = K \cdot \frac{F}{h^2}$$

(1)

where

- $F$—loading value (N);
- $h$—total immersion depth of the cone (m);
- $K$—cone constant, dependent on the cone angle $\alpha$ at the apex.

2.5. Determination of Water-Binding Capacity

The method used for determination of the water-binding capacity was based on the release by the test sample with light pressing, sorption of the released water with filter paper...
(Whatman, qualitative grade 1, 150 mm), and determination of the amount of separated moisture by the size of the spot area left by it on the filtered paper [15].

2.6. Determination of Energy Characteristics

Determination of energy characteristics of the grinder was carried out on the measuring stand. The stand consists of an electricity meter SO-E411 ("Asia Electric" LLP, Almaty, Kazakhstan) for determining the passive power consumption; an electric switch designed to turn the experimental unit on and off; an electric socket to connect the experimental unit; and a voltmeter, an ammeter, and a phase meter (a device for measuring \( \cos \varphi \)) to determine the active power of the electric motor. During the experiment, the machine was connected to the test bench for measuring current \( I \), voltage \( U \), and \( \cos \varphi \) while the machine was operating.

2.7. Microstructure Analysis

To determine the bone particle size, we observed the microstructure of bone particles on the scanning electron microscope SEM “JSM-6390LV” (JEOL Company, Tokyo, Japan). To prepare the meat–bone paste for scanning, the sample was heated in a boiling water bath and treated with 2% NaOH for full decomposition of meat tissue. After heating the solution, it was passed through a filter. The remaining bone particles were dried at 103–105 °C during 15 min in the drying oven. Then, the dried bone particles were observed on the microscope.

2.8. Statistics

In total, 16 samples (\( n = 48 \)) of bone mass (5 kg each) were ground on the grinder while varying knife rotation speed and gap between the knives. All measurements were performed in triplicate, and all results have been expressed as mean ± standard errors. The results of measurements were analyzed using Excel-2016 and Statistica 12 PL software (StatSoft, Inc., Tulsa, OK, USA). The differences between the samples were evaluated using a one-way ANOVA; \( p < 0.05 \) was considered statistically significant.

3. Results and Discussion

3.1. Change of Yield Stress, Water-Binding Capacity of Ground Meat, and Energy Characteristics of Grinder Depending on Knife Rotation Speeds and Clearance

The data on changes in yield stress, water-binding capacity, and energy characteristics depending on knife rotation speed and gap between the knives are presented in Table 2. From Figures 5 and 6, it is revealed that the highest values of yield stress and water-binding capacity are observed when the rotation speed of the knives is 4000 rpm and the clearance between the knives is 0.16 mm.

The analysis of the graphs of dependencies of yield stress and water-binding capacity on the rotational speed of the working bodies reveals that these parameters also increase with increasing rotational speed. This can be explained by the fact that with increasing rotation speed of the knives, more intensive cutting of particles of meat and bone raw materials takes place. The total surface of the minced meat particles increases, the moisture from the free form transforms into the surface-bonded form, the process of formation of a new structure of minced meat occurs and, as a consequence, the value of the yield stress and water-binding capacity increase.

The changes of yield stress and water-binding capacity from the clearance value between the rotating and stationary knives at different rotational speeds were studied. The analysis of the research results shows that these values increase up to the maximum values at a gap of 0.15 mm, and then decrease, regardless of the rotation speed. At this gap, the ratio of ground particles to moisture reaches optimal values. The moisture is maximally bound by proteins from the ground meat and bone raw materials. As the gap increases, the amount of water increases in relation to the proteins that bind them, and the values of yield stress and water-binding capacity decrease. Reducing the gap causes release of
intercellular juice and increases the liquid fraction in relation to proteins of meat and bone raw materials. The values of the yield stress and water-binding capacity are also decreased.

Table 2. Changes in yield stress, water-binding capacity, and energy characteristics depending on knife rotation speed and gap between the knives.

| Knife Rotation Speed (rpm) | Gap between the Knives (mm) | Yield Stress (Pa) | WBC (%) | Energy Characteristics (kW) |
|---------------------------|-----------------------------|-------------------|---------|----------------------------|
| 1000                      | 0.05                        | 704.74 ± 12.09 a  | 64.43 ± 0.69 | 3.50 ± 0.06 a               |
|                            | 0.16                        | 742.43 ± 9.74 a   | 64.71 ± 0.90 | 2.83 ± 0.05 b              |
|                            | 0.27                        | 666.72 ± 8.58 a   | 64.05 ± 0.61 | 2.59 ± 0.03 b              |
|                            | 0.38                        | 635.87 ± 7.02 b   | 63.83 ± 0.63 | 2.36 ± 0.02 b              |
| 2000                      | 0.05                        | 743.82 ± 11.92 a  | 65.13 ± 0.96 | 3.60 ± 0.07 a              |
|                            | 0.16                        | 781.23 ± 8.39 a   | 65.30 ± 1.18 | 2.98 ± 0.05 b              |
|                            | 0.27                        | 711.24 ± 14.17 a  | 64.73 ± 0.68 | 2.67 ± 0.04 b              |
|                            | 0.38                        | 676.91 ± 10.36 b  | 64.53 ± 1.17 | 2.42 ± 0.05 b              |
| 3000                      | 0.05                        | 816.64 ± 12.52 a  | 65.97 ± 1.36 | 3.69 ± 0.06 a              |
|                            | 0.16                        | 844.89 ± 14.74 a  | 66.17 ± 0.50 | 3.08 ± 0.04 b              |
|                            | 0.27                        | 779.95 ± 18.01 a  | 65.43 ± 0.63 | 2.74 ± 0.03 b              |
|                            | 0.38                        | 742.21 ± 14.85 b  | 65.23 ± 1.07 | 2.48 ± 0.04 b              |
| 4000                      | 0.05                        | 908.68 ± 9.11 a   | 66.86 ± 0.96 | 3.81 ± 0.06 a              |
|                            | 0.16                        | 943.29 ± 15.89 a  | 66.98 ± 1.13 | 3.20 ± 0.03 b              |
|                            | 0.27                        | 866.42 ± 15.03 a  | 66.44 ± 0.73 | 2.93 ± 0.04 b              |
|                            | 0.38                        | 827.82 ± 12.34 b  | 66.28 ± 0.54 | 2.64 ± 0.05 b              |

\(^{a,b}\) means within the same row with different uppercase letters differ significantly among different samples \((p < 0.05)\).

Figure 5. Variation of the yield stress from the gap and the knife rotation speed.
Figure 6. Variation of the water-binding capacity from the gap and the knife rotation speed.

The power consumption of the motor increases as the gap decreases. This can be explained by the fact that with a decreasing gap between the knives, the grinding process is intensified and the friction between the product and the knives increases, which, according to the Rebinder theory, leads to an increase in energy consumption [16,17]. When analyzing the data of power changes, it is clear that increasing the rotation speed of the working bodies together with reducing the gap between the knives corresponds to an increase in power consumption by the electric motor of the machine. So, if the power is 2640 kW at a rotation speed of 4000 rpm and a gap of 0.38 mm, then decreasing the gap to 0.05 mm increases the power to 3806 kW. It can be concluded that increasing the rotation speed of the working bodies and reducing the gap between the knives corresponds to an intensification of the process of fine grinding of meat and bone raw materials [18,19].

3.2. Determination of Particle Size Distribution of Bone Inclusions after Fine Grinding of Meat and Bone Raw Materials

To identify the changes in the particle size distribution of bone particles in the meat and bone raw material, we plotted the size distribution of bone particles in the meat and bone raw material at different knife rotation speeds and clearances.

From the graph of particle size distribution of bone inclusions in meat and bone raw material, we can see that in the distribution of bone particles by size depending on the speed of rotation and the gap between the knives, more than 80% of particles smaller than 100 microns were obtained (Figure 7) [20].
Figure 7. Change of particle size distribution of bone inclusions in meat and bone paste at different gaps between knives of the grinder.

Figure 8 shows images of bone particles magnified by 50 and 220 times, where bone particles were measured. Among the many measurements, there were no particle sizes larger than 0.1 mm (100 microns) detected.
4. Conclusions

Physical and structural–mechanical properties are one of the most important factors influencing the quality of fine grinding of chicken bones. The value of yield stress and water-binding capacity in fine grinding of chicken bones is also influenced by kinematic parameters—the rotation speed of knives and the gap between movable and fixed knives of rotary grinder. The identified dependence of the change of yield stress and water-binding capacity shows that by increasing the rotation speed of knives up to 4000 rpm and by changing the gap to 0.16 mm, these indicators reach their maximum values. When the gap is reduced, the yield stress and water-binding capacity increase. This can be explained by the fact that when the gap between the knives is reduced, the bone mass is ground more intensively, and the moisture from the free form turns into a surface-bound one. However, when the gap is less than 0.16 mm, the value of the yield stress and water-
binding capacity decreases due to the overgrinding of connective tissue; in addition, the temperature increases slightly, and the quantity of the smallest particles increases.

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