Energy-saving technology for fine grinding of food raw materials frozen in blocks

Boris Kapovsky[1 *], *Tatyana* Kuznetsova[1], *Anton* Lazarev[1] , and *Pavel* Plyasheshnik[2]

[1]V.M. Gorbatov Federal Research Center for Food Systems of Russian Academy of Sciences, 26, Talalihina Street, Moscow, 109316, Russia

[2]Moscow State University of Food Production, 11, Volokolamskoe Highway, Moscow, 125080, Russia

Abstract. Reducing the cost of electricity consumed when cutting frozen raw materials in the meat processing industry can significantly improve profitability and other economic indicators. The possibility of energy saving in the innovative technology of one-stage fine grinding of food raw materials was studied. The selected frozen meat blocks (beef and pork) and collagen-containing raw materials (meat cuttings and tripe) were ground to the required degree usingan experimental IBF-1 grinder. At the same time, the active three-phase power consumed by the electric motor of the cutting mechanism drive was measured and recorded. The study results showed that the IBF-1 grinder (milling method) could replace three machines (frozen meat cutter, meat comminutor, and micro cutter) with sequential grinding in three stages according to the standard grinding technology. The calculations carried out on the power costs per ton of products confirm that grinding requires 2.6 times less than the total installed capacity of meat-cutting machines of the standard technological chain.

1 Introduction

The researchobjective was to study the fundamental possibility of creating an energy-saving technology for one-stage fine grinding of food raw materials frozen in the form of blocks. As a result of reducing the standard process chain, usually used in the meat processing industry when cutting frozen raw materials, it is possible to achieve significant savings in the energy consumed for this process. This increases the economic performance of meat production. Reducing the equipment stock of meat-cutting machines (instead of three machines, one machine is used for fine grinding of frozen raw materials) will allow meat-processing plants to direct the released funds to develop their production. The proposed technology can be used for grinding various frozen raw materials processed in the food industry.

2 Materials and methods

Experimental frozen meat blocks were used as raw materials for grinding, cut from a block of meat of industrial standard size (second-class beef, hereinafter referred to as "beef";

* Corresponding author: b.kapovski@fncps.ru

semi-fat pork, hereinafter referred to as "pork"). The dimensions of the experimental blocks having the form of parallelepipeds were 0.075 m – width, 0.070 m – height, 0.3-0.4 m – length. Frozen collagen-containing raw materials (meat cuttings and tripe), formed as blocks of the above sizes in a mold (Fig. 1), were also ground.

Fig. 1. Mold.

The raw material temperature before grinding in the depth of the block was minus 12 □ – minus 14 □; on the block surface minus 4 □ – minus 6 □.

As a result of the microstructural study, the particle sizes of the ground raw materials were determined. Microstructural studies of ground raw materials were carried out following GOST 31479-2012 "Meat and meat products. Method of histological identification of the composition". Histological preparations were made on a freezing microtome MIKROM HM 525. The sections were studied using a light microscope Axio Imager. A1 (Carl Zeiss, Germany) using computer software for image analysis.

During grinding of frozen blocks of raw materials, using an industrial analyzer-recorder AFM-3192 (Fig. 2), the active three-phase power consumed by the electric motor of the cutting mechanism drive of the experimental grinder IBF-1 (milling block grinder modification 1) was measured and recorded in the operating mode. The measurements were carried out according to the scheme shown in Fig. 3.

Fig. 2. Industrial analyzer-recorder AFM-3192.

The current measuring pliers of the analyzer-recorder were connected to the power terminals of the control cabinet that completed the IBF-1 installation. The potential wires of the device were connected to the phase terminals of the stator winding of the electric motor of the cutting mechanism drive of the IBF-1 installation. The measurements were carried out according to the "three-phase – neutral" scheme. Statistical analysis of the energy consumed when milling frozen meat with a milling cutter was carried out by calculating estimated numerical characteristics (mathematical expectation and variance) of the experimental distribution of the active power consumed by the electric motor of the cutting mechanism drive of the IBF-1 installation when grinding raw materials. Verification of the correspondence of the law of experimental power distribution as a random variable to the proposed hypothetical distribution law was carried out according to the Pearson agreement criterion.

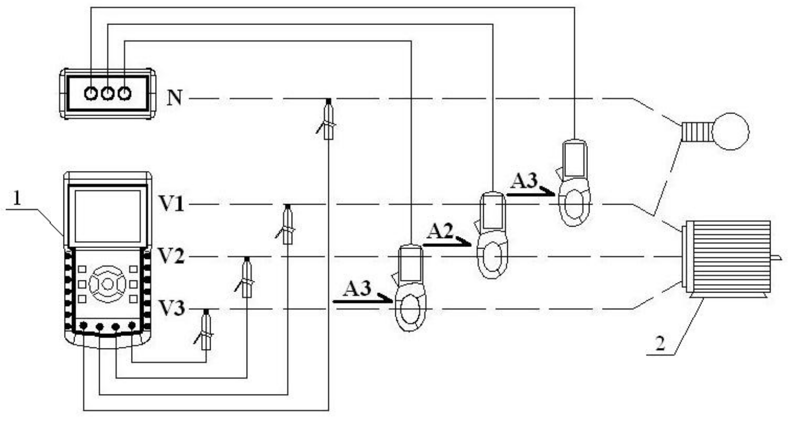

Fig. 3. Diagram of measuring the power consumption by the electric motor of the cutting mechanism drive of the IBF-1 grinder in the operating mode (1 – power analyzer AFM-3192, 2 – electric motor of the cutting mechanism drive).

3 Results and discussion

Figs. 4a and 4b show the microstructures of samples of ground meat.

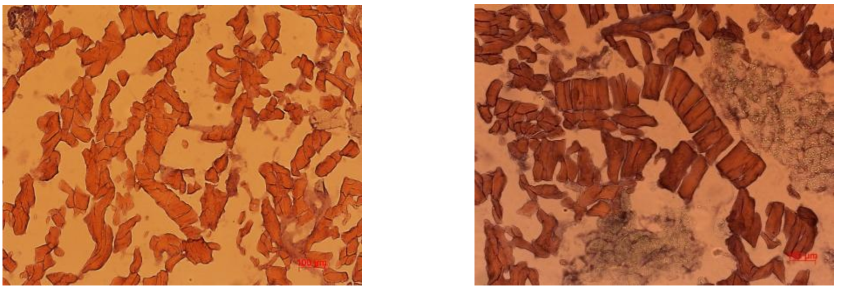

Fig. 4. Beef sample (left plot-4a) and pork sample (right plot-4b).

Statistical analysis of the chipped meat size (thickness and width) obtained from grinding raw materials was carried out according to the standard method [1,2]. Grouped statistical series were formed from the sizes of each type; histograms of the numerical distribution of the size hits in the selected ranges of their values were constructed; histograms of the density of the size distribution frequency in the selected ranges of their values were constructed. Calculations of estimated numerical characteristics of experimental distributions of chipped meat sizes give the following results:

for beef

$$m_a^* = \sum_{i=1}^{k} a_{iav} \cdot p_i^* = 42.28(\mu\text{m}) \tag{1}$$

$$\sigma_a^* = \sqrt{D_a^*} = \sqrt{\alpha_2 - (m_a^*)^2} = 15.86(\mu\text{m}) \tag{2}$$

$$m_b^* = \sum_{i=1}^{k} b_{iav} \cdot p_i^* = 166.64(\mu\text{m}) \tag{3}$$

$$\sigma_b^* = \sqrt{D_b^*} = \sqrt{\alpha_2 - (m_b^*)^2} = 90.48(\mu\text{m}) \tag{4}$$

for pork

$$m_a^* = \sum_{i=1}^{k} a_{iav} \cdot p_i^* = 118.99(\mu\text{m}) \tag{5}$$

$$\sigma_a^* = \sqrt{D_a^*} = \sqrt{\alpha_2 - (m_a^*)^2} = 61.15(\mu\text{m}) \tag{6}$$

$$m_b^* = \sum_{i=1}^{k} b_{iav} \cdot p_i^* = 495.28(\mu\text{m}) \tag{7}$$

$$\sigma_b^* = \sqrt{D_b^*} = \sqrt{\alpha_2 - (m_b^*)^2} = 245.57(\mu\text{m}) \tag{8}$$

where m_a^*, m_b^* – the estimates of the mathematical expectation of the experimental distributions of the thickness and width of the chipped meat, respectively; σ_a^*, σ_b^* – estimates of the mean square deviation of the experimental distributions of the thickness and width of the chipped meat, respectively; D_a^*, D_b^* – estimates of the variance of the experimental distributions; k – the number of ranges; p_i^* – the frequency of falling into the i-th range; a_{iav}, b_{iav}– the average values of the thickness and width of the chipped meat in the$i$-th range, respectively; α_2 – the initial moment of the second order of the experimental distributions of the thickness and width of the chipped meat.

The thickness is a smaller size of chipped meat, and the width is a larger size. The beef was ground with a fine-tooth cutter according to GOST 29092-91 with the following cutting mode parameters: the feed rate of raw materials to the cutter was 0.0243 m/s, the cutter rotation speed was 2289.14 min^{-1}. The pork was ground with a large-tooth milling cutter per GOST 29092-91 with the following parameters of the cutting mode: the feed rate of raw materials to the cutter was 0.0243 m/s, the cutter rotation speed was 2289.14 min^{-1}.

Table 1 shows the measurement data of the active three-phase power consumed by the electric motor of the cutting mechanism of the IBF-1 grinder in the operating mode when equipped with a milling cutter with a small tooth GOST 29092-91. The measurement data presented in Table 1 were obtained by grinding different experimental blocks of frozen meat of two types (beef and pork). Next, the power measurement data will be considered as a single statistical data sample.

Table 1. Power measurement data

Power consumption when grinding beef, kW	**Power consumption when grinding pork, kW**
2.896; 3.500; 2.560; 1.996; 1.996; 1.029; 1.536; 3.334; 2.630; 3.088; 2.054; 2.896; 3.713; 4.179; 4.099; 3.548; 2.322; 4.329; 4.067; 4.046; 2.437; 2.695; 2.653; 2.430; 1.876; 2.698	3.335; 3.418; 3.441; 3.154; 3.502; 3.306; 3.903; 4.174; 3.627; 4.035

The data presented in Table 1 were obtained at the following values of the cutting mode parameters: the feed rate of the raw material to the cutter was 0.0243 m/s, the cutter rotation speed was 2289.14 min^{-1}.

Statistical analysis of the experimental procedure data was carried out according to the above-mentioned method. Estimate calculations of the numerical characteristics of the experimental power distribution consumed in the grinding process give the following results:

$$m_N^* = \sum_{i=1}^{k} N_{iav} \cdot p_i^* = 3.07(kW) \tag{9}$$

$$\sigma_N^* = \sqrt{D_N^*} = \sqrt{\alpha_2 - (m_N^*)^2} = 0.789\ (kW) \tag{10}$$

where m_N^*– the estimate of the mathematical expectation of the experimental distribution; σ_N^* – the estimate of the mean square deviation of the experimental distribution; D_N^* – the estimate of the variance of the experimental distribution; k – the number of ranges; p_i^* – the frequency of falling into the i-th range; N_{iav} – the average power value in the$i$-th range; α_2– the initial moment of the second order of the experimental distribution of the power consumed during the grinding process.

Let us hypothesize that the experimental statistical distribution of power consumption by the electric motor of the cutting mechanism drive of the IBF-1 grinder obeys the normal law with the parameters calculated above:

$$f(a) = \left[\frac{1}{(\sigma\sqrt{2\pi})}\right] \cdot exp\left[-\frac{(a-m)^2}{(2\cdot\sigma^2)}\right] = \left[\frac{1}{(0.789\cdot\sqrt{2\pi})}\right] \times exp[-(a-3.07)^2/(2\cdot 0.622)] \tag{11}$$

Let us check the plausibility of the hypothesis using the Pearson agreement criterion.

Table 2 shows the probabilities of the power falling into the ranges of its values, calculated from a hypothetical distribution.

Table 2. Probabilities of the power values falling within the selected ranges according to the hypothetical distribution

Power range limits, kW	1.00-2.00	2.00-2.60	2.60-3.20	3.20-3.60	3.60-4.40
Probability	0.0824	0.1873	0.2933	0.1811	0.2059

Calculate the value of the Pearson criterion:

$$\chi^2 = \sum_{i=1}^{k} [(n_i - n \cdot p_i)^2/(n \cdot p_i)] \cong 3.70 \tag{12}$$

where i–the number of the power values range; k – the number of ranges; n_i – the number of power values in the$i$-th range; n – the number of measurements, $n = 36; \sum n_i = n; p_i$ – the probability of the power value falling into the hypothetical distribution in the i-th range.

The table value of the Pearson criterion for the significance level of 0.1 under three independent conditions and the number of degrees of freedom $r = k - 3 = 5 - 3 = 2$ is [3]: $\chi^2_{table} = 4.60$. Thus, under the accepted conditions, the calculated value of the Pearson criterion is less than the table value (3.70 <4.60). Therefore, the hypothesis of the normal distribution of the active power consumed by the electric motor of the drive of the cutting mechanism of the IBF-1 grinder during the grinding process as a random variable can be considered not contradicting the experimental data. The alignment of the experimental distribution with the hypothetical normal distribution is shown in Fig. 5.

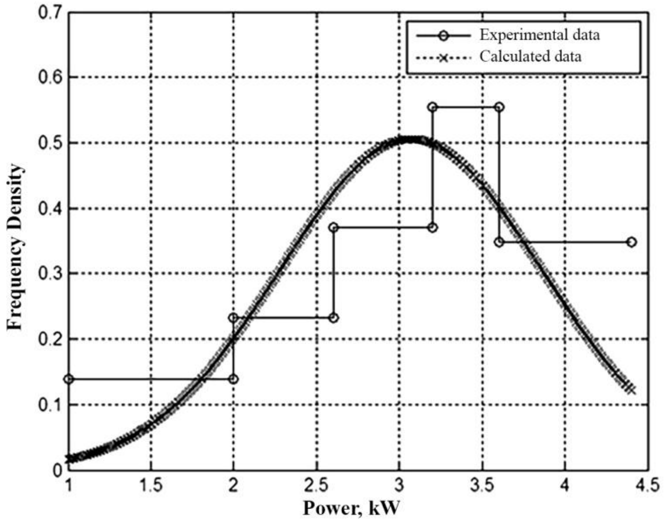

Fig. 5. Graphs of electrical power frequency density.

The results of the calculations allow assuming, based on the central limit theorem [4], that stochastic factors (heterogeneity of raw materials in terms of texture and structural characteristics, changes in the temperature of raw materials in the volume of a meat block) have an equivalent effect on the energy consumption of the milling process of block frozen meat.

When conducting a microstructural study of collagen-containing raw materials (meat cuttings), ground by the milling method, the following results of statistical analysis of the size of the resulting chips were noted:

The average size of the connective tissue chip thickness is 146.56 μm with a mean square deviation (msqd) from the average size of 92.41 μm. Here and further, the average size was defined as the arithmetic mean of the sizes included in the sample – the sample average. The average size of the connective tissue chip width is 647.84 μm with an msqd of 380.40 μm. The average size of the chip thickness of meat inclusions is 99.61 μm with an msqd of 63.57 μm. The average size of the chip width of meat inclusions is 439.80 μm with an msqd of 224.87 μm. The number of dimensions of the width of the connective tissue chips that exceeded 1 mm is 9.38% of the sample size; no corresponding exceedances of the chip thickness were found. The number of dimensions of the chip width of meat inclusions exceeding 1 mm is 1.82% of the sample size; no corresponding excess of the chip thickness was detected. The average size of the fragments of connective and adipose tissue that were not included in the sample, measured by the fragment diameter, is 502.69

μm with an msqd of 283.50 μm. The number of sizes of these fragments exceeding 1 mm is 6.49% of their total number.

The collagen-containing raw material (tripe) was ground with a multi-blade tool (milling cutter). The results of the statistical analysis of the size of the resulting chips are as follows:

The average size of the connective tissue chip thickness is 73.67 μm with an msqd of 43.95 μm. The average size of the width of the connective tissue chip (tripe) is 179.07 μm with an msqd of 101.86 μm. The excess size of the thickness and width of the connective tissue chips of the value equal to 1 mm was not detected. The average size of the fragments of connective and adipose tissue that were not included in the sample, measured by the fragment diameter, is 281.34 μm with an msqd of 151.19 μm. No excess of the size of these fragments of the value equal to 1 mm was detected.

Table 3 shows the measurement data of the active three-phase power consumed by the electric motor of the cutting mechanism of the IBF-1 grinder in the operating mode when it is equipped with a cutter with carbide plates when grinding meat cuttings. Table 4 shows similar data when grinding the tripe. The grinding mode in both cases was determined by the following parameters: the rotation speed of the milling cutter 2289.14 min^{-1}; the feed rate of the raw material block to the grinding zone 0.0243 m/s.

Based on the data given in Tables 3 and 4, grouped statistical series are formed (Table 5 and 6, respectively).

Table 3. Measurement data of the active power consumed by the electric motor of the cutting mechanism of the IBF-1 grinder in the operating mode (grinding of meat cuttings).

Power consumption when grinding meat cuttings, kW
2.970; 2.990; 2.890; 2.555; 2.786; 2.790; 2.000; 2.670; 3.100; 3.280; 2.800; 2.750; 3.350; 3.550; 3.450; 3.688; 3.250; 4.100; 4.100; 4.250; 3.500; 3.255; 2.960; 2.890; 2.900; 3.000

Table 4. Measurement data of the active power consumed by the electric motor of the cutting mechanism of the IBF-1 grinder in the operating mode (tripe grinding).

Power consumption when grinding tripe, kW
3.500; 3.550; 3.250; 3.150; 3.650; 3.650; 3.450; 4.250; 4.200; 4.250

Table 5. Grouped statistical series of data for measuring the power consumption of the electric motor drive of the cutting mechanism IBF-1 (meat cuttings).

Range and its boundaries in kW	Number of power values in the range	Frequency of hits in the range p_i^*	Average power value in the N_{iav}, kW range
2.00-2.50	1	0.038	2
2.50-3.00	12	0.462	2.829
3.00-3.50	7	0.269	3.241
3.50-4.00	3	0.115	3.579
4.00-4.50	3	0.115	4.15

Table 6. Grouped statistical series of data for measuring the power consumption of the electric motor of the cutting mechanism drive IBF-1 (tripe).

Range and its boundaries in kW	Number of power values in the range	Frequency of hits in the range p_i^*	Average power value in the N_{iav}, kW range
3.00-3.50	3	0.3	3.283
3.50-4.00	4	0.4	3.588
4.00-4.50	3	0.3	4.233

 https://doi.org/10.1051/e3sconf/202127903009

According to the data given in Table 5, let us construct a histogram of the numerical distribution of the power consumed by the electric motor of the cutting mechanism drive of IBF-1 installation in the selected ranges of its values (Fig. 6.). Let us construct a similar histogram for the data given in Table 6 (Fig. 7). Next, let uscalculate the frequency densities f_i^* from the ranges of power consumption values for both cases of grinding of collagen-containing raw materials (Table 7 – grinding of meat cuttings; Table 8 – tripe grinding).

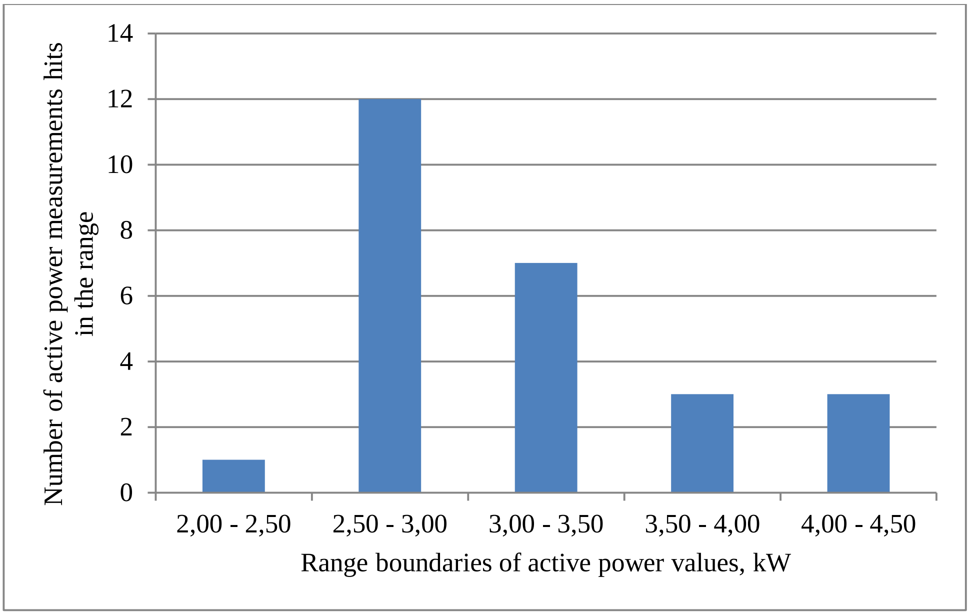

Fig. 6. Histogram of the numerical distribution of the power consumption of the electric motor drive of the cutting mechanism IBF-1 in the selected ranges of its values (grinding of meat cuttings).

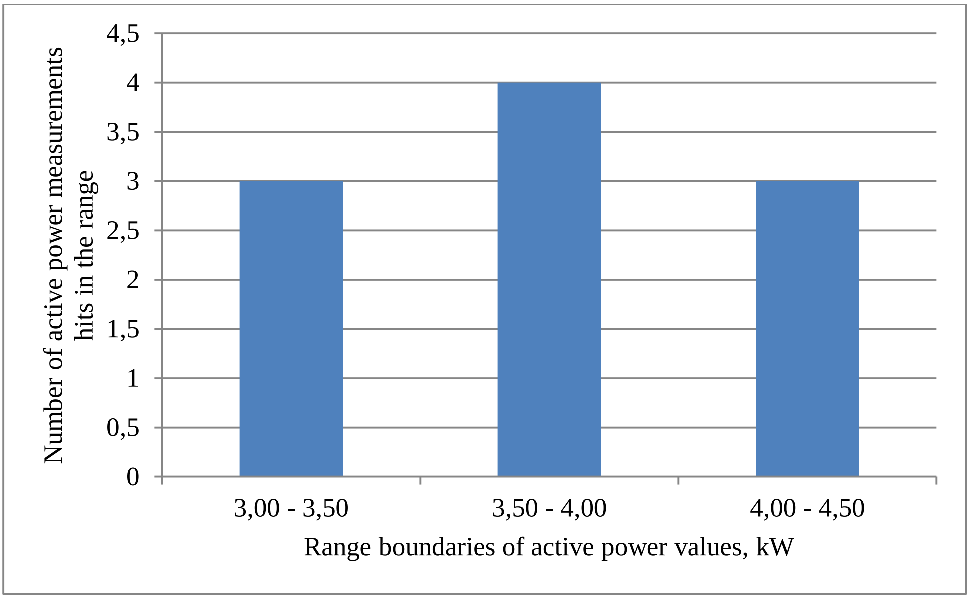

Fig. 7. Histogram of the numerical distribution of hits of the value of the power consumed by the electric motor of the cutting mechanism IBF-1 in the selected ranges of its values (tripe grinding)

Table 7. Frequency densities f_i^* by power consumption ranges (meat cuttings).

Range limits of power values, kW	2.00-2.50	2.50-3.00	3.00-3.50	3.50-4.00	4.00-4.50
Frequency density f_i^* ×10^{-2}, kW^{-1}	7.692	92.308	53.846	23.077	23.077

Table 8. Frequency densities f_i^* by ranges of power consumption values (tripe).

Range limits of power values, kW	3.00-3.50	3.50-4.00	4.00-4.50
Frequency density f_i^* ×10^{-2}, kW^{-1}	0.6	0.8	0.6

Let uscalculate the estimates of the numerical characteristics of the experimental power distributions consumed in the process of grinding collagen-containing raw materials:

for meat cuttings

$$m_{N1}^* = \sum_{i=1}^{k} N_{iav} \cdot p_i^* = 3.147(kW) \tag{13}$$

$$\sigma_{N1}^* = \sqrt{D_N^*} = \sqrt{\alpha_2 - (m_N^*)^2} = \ 0.487(kW) \tag{14}$$

for tripe

$$m_{N2}^* = \sum_{i=1}^{k} N_{iav} \cdot p_i^* = 3.690(kW) \tag{15}$$

$$\sigma_{N2}^* = \sqrt{D_N^*} = \sqrt{\alpha_2 - (m_N^*)^2} = \ 0.377(kW) \tag{16}$$

where m_N^* – the estimate of the mathematical expectation of the experimental distribution; σ_N^* – the estimate of the mean square deviation of the experimental distribution; D_N^* – the estimate of the variance of the experimental distribution; k – the number of ranges; p_i^* – the frequency of falling into the i-th range; N_{iav} – the average power value in the$i$-th range; α_2 – the initial moment of the second order of the experimental distribution of the power consumed during the grinding process.

The obtained estimates of the numerical characteristics of the experimental power distributions during the grinding of frozen raw materials (meat and collagen-containing raw materials) can be used to calculate the installed power of the electric drive of the cutting mechanism of a pilot industrial sample of a milling grinder. Let usassume that the IBF-1 installation is equipped with a cutter with a small tooth with a D = 160 mm diameter and a length of 250 mm as per GOST 29092-91. Then, following the calculation of the power consumed when grinding raw materials, let uschoose an electric motor to drive the cutting mechanism of the AIR160M2 type with a P_{rat} = 18.5 kW. The power was calculated based on the specific force of the raw material cutting process, determined based on experimental data. The size of the ground meat particles obtained as a result of grinding frozen meat blocks with a size of (0.3...0.4)×0.070×0.075 m in one stage on the IBF-1 installation when equipped with a milling cutter with a small tooth is in the range of 0.2-0.4 mm. Three machines are required with sequential grinding in three stages to obtain a product with the same degree of grinding according to the standard technology: fine grinding (medium grinding), meat comminutor (fine grinding), microcutter (cutter) – extra fine grinding. Table 9 shows the main technical characteristics of the IBF-1 grinder in comparison with the specified meat-cutting machines for the same performance (2000 kg/hour – in the case of completing the experimental grinder with a cylindrical nozzle cutter with a small tooth with a diameter of 160 mm and a length of 250 mm, that is, a cutter with the maximum dimensions according to GOST 29092-91).

Table 9. Technical characteristics of meat cutting machines.

Machine name	Feedstock tempera-ture, ℃	Raw material particle size at the output of the machine, mm	Installed power, kW	Capacity, kg/hour	Dimen-sions, mm	Weigh t, kg
KILIA SP-50 frozen meat cutter	-25	100 pieces of meat	15	1000-4000	1245× 1800× 2450	2500
KILIA 2000 S E130 meat com-minutor	-25…-5	3	19.5	up to 2700	2700× 2440× 1380	650
KILIA Fine CUT 1000/2000 microcutter	2…4	0.3	30	2000	1800× 860× 1300	745
Experimenta l grinder IBF-1	-25…-5	0.2-0.4	19.05	1978.97 (estimated)	945× 1080 1825	305

Note. The installed capacity of the IBF-1 grinder considers the power of the drive for feeding raw materials to the grinding area.

It is necessary to consider a minced meat mixer of the same performance together with the IBF-1 grinder for correct comparison of the technical characteristics of the equipment specified in Table 9. Choose a K7-FM-150 minced meat mixer with the following technical characteristics: capacity 2000-2500 kg/hour; installed capacity no more than 3 kW; overall dimensions 1480×730×1160 mm; weight no more than 460 kg.

The total installation power of the KILIA SP-50 frozen meat cutter, the KILIA 2000 S E130 meat comminutor, and the KILIA Fine CUT 1000/2000 microcutter is 64.50 kW. The total installed capacity (estimated) of the IBF-1 grinder and the K7-FM -150 minced meat mixer is 22.05 kW, 42.45 kW less than the total installed capacity of standard meat cutting machines listed in Table 9. The total weight of the KILIA SP-50 frozen meat cutter, KILIA 2000 S E130 meat comminutor, and KILIA Fine CUT 1000/2000 microcutter is 3895 kg. The total weight of the IBF-1 grinder and the K7-FM-150 minced meat mixer is 765 kg, which is 3130 kg less than the total weight of the above-mentioned serial meat-cutting machines. The total geometric volume of the KILIA SP-50 frozen meat cutter, the KILIA 2000 S E130 meat comminutor, and the KILIA Fine CUT 1000/2000 micro cutteris16.59 m^3. The total geometric volume of the IBF-1 grinder and the K7-FM-150 minced meat mixer is 3.11 m^3, which is 13.48 m^3 less than the total geometric volume of the machines of the standard technological chain.

If the grinder is equipped with a set of milling cutters of the same standard size, mounted sequentially on one shaft ("milling shaft"), the productivity of the raw material cutting process can be significantly increased when grinding blocks of frozen food raw materials of the maximum linear dimensions provided for in the regulatory documentation for these types of raw materials. The installed drive power of the grinder cutting mechanism must be calculated for these operating conditions. It should be noted that GOST 29092-91 provides for the production of cylindrical attachment cutters with small and large teeth made of 9XC steel according to GOST 5950, which is allowed for contact with food media.

4 Conclusion

Experimental studies have proved the possibility of one-stage fine grinding of blocks of frozen food raw materials (meat and collagen-containing meat raw materials) to produce chips with dimensions that do not exceed 1 mm. The total installed capacity of meat-cutting machines in the standard production chain per ton of product exceeds the corresponding capacity for milling by 2.6 times. This leads to significant savings in electricity consumption for cutting raw materials, which occupies a significant share in the energy balance of meat processing enterprises (according to some estimates – up to 50%; only energy consumption for refrigeration equipment can compete in this sense).

The milling method can be used for fine grinding of other food raw materials frozen in blocks: cottage cheese, vegetable raw materials, fish. Thus, onecan count on creating a universal module of cutting equipment that implements energy-saving technology for grinding various types of raw materials for the needs of the food industry.

Obtaining chips of ground raw materials of the specified sizes allows creating an intelligent control system for the technological process of food production with functional and technological characteristics ensuring the guaranteed high quality.

References

1. Gaidyshev I., Data analysis and processing: a special reference book (Saint Petersburg: Piter, 2001)
2. Vukolov E. A., Fundamentals of statistical Analysis (Moscow: FORUM, 2008)
3. Protasov K. V., Statistical analysis of experimental data (Moscow: Mir, 2005)
4. Kobzar A. I., Applied mathematical statistics. For engineers and researchers (Moscow: FIZMATLIT, 2006)