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The extrusion process of poly-cereal mixtures: study and calculation of the main parameters

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ABSTRACT

Theoretical prerequisites for the extrusion of bulk components for the production of high-readiness products have been developed, which formed the basis for calculating and optimizing the main technological parameters of the extrusion process. It has been experimentally confirmed: firstly, the design parameters of the extruder and the initial humidity of the poly-cereal mixture have the greatest influence on the melt pressure of the product; secondly, the geometric characteristics of the working body, the frequency (speed) of the screw rotation and the pressure of the product maximally affect the temperature in the pre-matrix zone of the extruder. It was found that an increase in the rotation speed of the working organ (screw) from 80 to 250 min⁻¹ leads to the highest value of the optimization criterion – the energy value of a poly-cereal food product of a high degree of readiness, respectively, for the poly-cereal mixture Fitness – 332.34 kcal and the poly-cereal mixture Health – 334.09 kcal.

Keywords: calculation, extrusion, extrudate, poly-cereal, technological parameters

INTRODUCTION

Currently, the role of fast food products (ready-to-eat) and dietary, therapeutic, and preventive, health-improving products based on grain crops is sharply increasing in the population's diets. The demand for fast food products with high protein and dietary plant fibers has increased. The same is true with the main grains: corn and wheat is processed mainly for flour and cereals, and oats have recently been used to produce oat flakes. Other grains are not used at all, except for the production of ordinary cereals [2], [4], [6], [8], [10], [12]. In this regard, the development of technology for producing high-readiness products based on poly-cereal mixtures balanced in the content of individual nutrients (fiber), vitamins, macro- and microelements with certain functional properties is an urgent task. Fast food has changed eating habits and has become one of the traditional forms of nutrition worldwide. They are very widely used by the population of many countries as ready-made breakfasts and healthy food products. For example, the USA's market for ready-to-eat foods and light snacks is growing by 3% annually. In our country, this demand and the demand for protein food products are met by imports. Extrusion technology is most often used for the preparation of fast food [2], [3], [10], [12]. During extrusion processing of starch and protein-containing raw materials, several advantages can be obtained compared to traditional technologies. These advantages consist in the fact that with single short-term processing of dry grain it is possible to obtain ready-to-eat products;

- to increase the digestibility of raw materials and the degree of their use;
- to reduce the microbial contamination of raw materials and neutralize the thermolabile anti-nutritional components of legumes.

Scientific Hypothesis

An increase in the rotation frequency of the working organ (screw) will increase the energy value of a poly-cereal food product with a high degree of readiness. Moreover, the influence of the moisture content of the processed poly-cereal flour mixture on the energy value of the finished product is insignificant.

MATERIAL AND METHODOLOGY

Samples

The following grain crops were identified as objects of study, which were conditionally divided into three groups:

- grain raw materials as scientific products of domestic breeders;
- bulk raw materials, flour from a whole ground grain of cereals and poly-cereal mixture based on it, which is a valuable source of nutrients and minerals;
- products of a high degree of readiness that strengthen the functional status, i.e., products of directed action with maximum preservation of biologically active substances concentrated in the peripheral parts of grain raw materials.

The samples of grain raw materials selected for the study comply with the requirements set out in the ST RK ISO 7970-2013 and GOST ISO 24333-2017 standards. At the same time, control and certification tests of prototypes were studied in the conditions of a testing laboratory or a certification body in the field of food production of Nutritest Academy of Nutrition LLP.

Chemicals

The chemical composition of the poly-cereal mixture (mass fraction of protein, starch and fiber content, ash content) was determined using an infrared analyzer. Chemicals were not used in this research.

Animals and Biological Material

this study, raw materials of plant origin were used (poly-cereals: based on grains of wheat, barley, rye, oats, buckwheat, corn and their composite mixtures).

Instruments

The research laboratory of the KazNARU Center for the extrusion of poly-cereal mixtures includes the following equipment: 1 – universal crusher DU-500 (Russian Federation); 2 – mixer of the poly-cereal flour mixture (China); 3 – twin-screw extruder LT 65L with control panel (China); 4 – filling filler (China) and 5 – micronizer UTZ-4 (Russian Federation).

Laboratory Methods

Extrusion is a special method of processing raw materials in which the flour mixture is amenable to mechanical action (grinding) on the screw part of the extruder. This process occurs under the influence of high temperatures (approximately 150 °C) and pressure. Furthermore, the crushed heated mass under high pressure falls under the influence of low pressure. As a result of a sharp drop, a so-called «explosion» occurs: the finished product increases in volume and acquires a porous structure.

When studying the process of mixing various poly-cereal mixtures, after the expiration of every 10 seconds, an experimental sample of a flour poly-cereal mixture was taken, where the chemical composition (protein, fiber, fat content) was determined by near-infrared spectroscopy, after which the caloric content of all organic compounds in the test sample was calculated according to the mathematical formula.

$$E_v = 4.0 \cdot x_p + 9.0 \cdot x_f + 3.75 \cdot x_c$$

Where:

E_v – energy value (calorie content); x_p , x_f and x_c – protein, fat and carbohydrate content (fiber + starch).

INFRAMATIC 8611/8620 infrared spectrometer was used to determine the chemical composition of the selected mixture sample to analyze ground grain and grinding products.

For rational construction of the technological production process of high-readiness products based on a poly-cereal mixture, the physicomechanical and biochemical properties of poly-cereal raw materials were studied, which assess the technological advantages of grain raw materials.

Description of the experiment: Experimental studies on the process of extrusion of a poly-cereal flour mixture were carried out under the conditions of the International Research Center «Technology of Food and Processing Industries» of the Kazakh National Agrarian Research University and the research laboratory of the Astana branch of the Kazakh Research Institute of Processing and Food Industry LLP.

Instrumental methods for studying the rheological properties of food products were used to determine the quality indicators, rheological properties (elasticity, extensibility, elasticity, energy intensity) of dough based on whole grain flour, as well as the safety of grain raw materials of Kazakhstan selection and flour from poly-cereal raw materials.

Studies were carried out in experimental installations to evaluate the efficiency of technological processes of grinding grain raw materials, mixing, and extrusion of a poly-cereal mixture.

The efficiency of the raw process of grinding grain raw materials in experimental facilities was evaluated by the following indicators: the degree of grinding (granulometric composition) of the objects of study, the productivity of the grinding device (Q , kg/hour), and the specific energy costs of conducting the grinding process (N , kWh/t).

The efficiency of the technological process of grinding grain raw materials depends on many factors. The humidity of the crushed material significantly affects (–the calculation of the degree of influence of the moisture content of the crushed material is reflected in the matrix of the multifactorial experiment according to Table 1) the efficiency of the technological process of processing grain raw materials. Also, the rotation frequency of the working body and the number of cycles of repeated processing has a significant impact (–the calculation of the degree of influence of the rotational speed of the working body and the number of reprocessing cycles are reflected in the matrix of the multifactorial experiment according to Table.1) on the efficiency of the grain processing process. Therefore, experimental studies were carried out at different values of the moisture content of the crushed grain and different rotational speeds of the working organ [16], [17], [18].

A preprepared experimental sample of the object of study (wheat, barley, oats, corn, buckwheat, and millet) weighing 10 kg is alternately loaded into the receiving device of the grinding plant and subjected to grinding at variable values of the rotational speed of the working bodies, the multiplicity of grinding, and the humidity of the crushed material.

In addition, the mixing process was investigated, which is a complex technological process, on the effectiveness of which the homogeneous distribution of all nutrients in any volume of the poly-cereal mixture depends.

As an indicator of the efficiency of the mixing process, variable values of the caloric content of the selected samples of the poly-cereal mixture were used, with fixed values of the mixing time and the rotation frequency of the working organ.

The efficiency of the mixing process was evaluated by controlling the following parameters: the values of the caloric content of selected samples of flour poly-cereal mixture (E_v , kcal) and the mixing time (t , sec) of the bulk components of the mixture, the rotation speed of the working organ (n , min^{-1}) at fixed values of the energy intensity of the mixing process.

The pre-prepared bulk components of the poly-cereal mixture are loaded alternately into the mixing tank of the device, then the installation starts. Experimental studies were carried out at various fixed values of the rotation speed of the mixer's working body. The rotation frequency n of the working body was changed by replacing the pulleys' diameter on the electric motor's driveshaft.

The results obtained from the experimental studies were entered into the tables of the Microsoft Excel word processor, based on which a graph was constructed of the dependence of the caloric content of the selected samples of flour poly-cereal mixture (E_v , kcal) and the mixing time (t , sec) of the bulk components of the mixture at different rotational speeds of the working organ (n , min^{-1}).

Next, the extrusion process was investigated, an important technological process for giving unique food and taste advantages to the products produced.

The methodology of conducting experimental studies on the study of the extrusion process is as follows. The pre-prepared poly-cereal mixture, by the developed recipe, is loaded into the receiving device of the experimental extruder. After that, the installation starts at fixed values of the rotation speed of the working body – the pressing screw. At the same time, variable values of pressure and temperature of the extrudate at the outlet of the matrix of the pressing screw are fixed.

Number of samples analyzed: we analyzed 27 samples.

Number of repeated analyses: repeated analyses = 3.

Number of experiment replication: triple.

Statistical Analysis

Mathematical statistics, methodological approach and methods of comparative analysis were used to conduct experimental studies. The obtained experimental data were processed by the methods of mathematical statistics in the STATISTICA editor and Microsoft Excel. The accuracy of the obtained experimental data was determined using the Student's t-test with a confidence probability of ≤ 0.05 with a set of parallel determinations of at least 5 (confidence probability $p = 0.95$). Linear programming tasks were solved using the *MS Excel* spreadsheet processor setting "Search for a solution" with the Excel Solver setting.

RESULTS AND DISCUSSION

In practice, the Ostwald-de Ville power equation is more often used to describe the flow of bulk material during extrusion [1], [5]:

$$\tau = \mu' \cdot \dot{\gamma}^n \tag{1}$$

Where:

τ – is the shear stress in the material; μ' – the consistency coefficient of the material; $\dot{\gamma}$ is the shear rate; n is the flow index.

The power law has become widely used to express the flow of various non-Newtonian materials [1], [5], [11], which is due to its simple mathematical form, the minimum number of rheological parameters (two), and a fairly good approximation of the results in practical use. It makes it easy to describe the rheological behaviour of the material.

This allows us to conclude that determining the rheological properties of the bulk mass in the extrusion process, which directly affects the quality of the finished product, is of considerable interest and is an urgent task at present.

While studying the flow of viscoplastic materials in channels of various shapes, the possibility of their movement with slippage on contact surfaces was found. At the same time, the physical meaning of the slippage phenomenon is not considered.

Hypothetically, the possibility of the pressed material slipping along the bottom of the screw channel was considered by Bostanjian and Stolin [5]. This hypothesis was confirmed by an experimental study of some modes of extrusion of grain components [9], [12], [15].

It was previously shown [4], [12], that the "piston" motion of the material pressed in a cylindrical channel can be represented as a layered flow when the viscosity of the boundary layer of the material is less than the viscosity of the core of the flow. We apply this approach to determine the rate of material slipping along the bottom of the screw channel.

Ignoring the influence of the blades, let's imagine the screw channel with two parallel planes correlated with the Cartesian coordinate system, as shown in Figure 1.

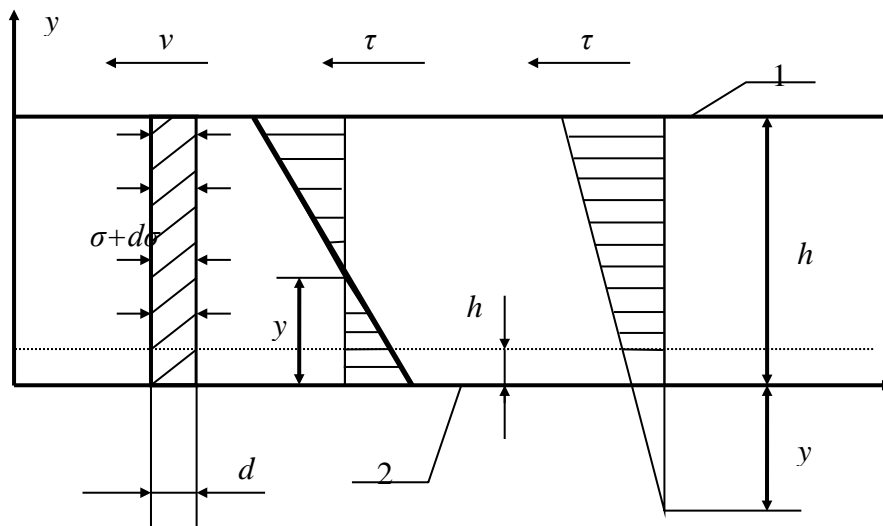


Figure 1 Diagram of the screw channel model. Note: 1 – plane replacing the bottom of the screw channel; 2 – plane replacing the screw cylinder.

The upper plate moves at a velocity v_c relative to the lower one. There is no material slippage on the upper plate, and tangential stress acts τ_c . Compression stresses modulo increase in the direction of velocity v_c .

The equilibrium equation for this case has the form (2) [1], [5]:

$$\tau_{xy} = \frac{d\sigma}{dx} (y - y_0) \tag{2}$$

Where:

τ_{xy} – is the shear stress in the pressed material; $\frac{d\sigma}{dx}$ – the gradient of normal stresses in the pressed material; y_0 – the coordinate of the plane on which the tangential stresses $\tau_{xy} = 0$.

Select a boundary layer with a thickness of h_n adjacent to the lower plate. A dotted line indicates the border of this layer (see Figure 1).

We assume the dependence of the shear stress τ_{xy} on the shear rate $\dot{\gamma}_x$ (velocity gradient $\frac{dv_x}{dy}$) in the boundary layer is satisfactorily described by the Oswald-de Ville equation [1], [11]. Then equation (1) is transformed into the form (3):

$$\tau_{xy} = \mu'_n \dot{\gamma}_x^{n_n} = \mu'_n \left(\frac{dv_x}{dy}\right)^{n_n} \quad (3)$$

Where:

μ'_n – is the consistency coefficient of the pressed material in the boundary layer; n_n is the index of the flow of the pressed material in the boundary layer.

The Ostwald-de Ville equations (1) and (3) are valid outside the boundary layer. At the same time, its parameters do not have a subscript [1], [5].

Denote the velocity of the material in the region $y \geq y_0$ by v_{x1} , and in the region. $y \geq y_0$ by v_{x2} .

Consider the motion of the material in the boundary layer when the velocity derivative changes its sign in the flow region between the plates outside the slip layer, that is, when the condition $h_n < y_0 < h_{uu}$ is met. For this case, equation (2), taking into account the dependence (3) in the region $0 < y_0 < h_n$, has the form (4) [1], [5], [11]:

$$\frac{dx_{x1}}{dy} = a_{wn} (y_0 - y)^{m_n} \quad (4)$$

Where:

$$a_{wm} = \left(\frac{1}{\mu'_n}\right)^{m_n} \left|\frac{d\sigma}{dx}\right|^{m_n}, \quad m_n = \frac{1}{n_n}$$

We assume the initial condition $v_{x1} = 0$ at $y = 0$ and, integrating equation (4) within the boundary layer, we obtain equation (5) [1], [5]:

$$v_{xn} = \frac{a_{wn}}{m_n+1} [y_0^{m_n+1} - (y_0 - h_n)^{m_n}] \quad (5)$$

For the case $y_0 < 0$, taking into account the direction of the tangential stress $\tau < 0$, equation (2) is transformed into equation (6) [1], [5]:

$$\frac{dv_{x2}}{dy} = a_{wn} (y - y_0)^{m_n} \quad (6)$$

Integrating it under the same conditions as equation (4), we obtain (7) [1], [5]:

$$v_{xn} = \frac{a_{wn}}{m_n+1} [(-y_0)^{m_n+1} - (h_n - y_0)^{m_n+1}] \quad (7)$$

Equations (5) and (6) allow us to determine the velocity of wall sliding in the boundary layer at a known thickness and rheological parameters of the pressed material.

It is possible to distribute tangential stresses in the pressed material at which $0 < y_0 < h_n$. For this case, the velocity of wall sliding is determined by solving the differential equation (3) under initial conditions $v_{x2} = 0$ at $y = 0$, and the differential equation (6) under initial conditions $v_{x2} = v_{xn}$ at $y = h_n$. Taking [1], [5]:

$$v_{x1} = v_{x2} \text{ at } y = y_0 \quad (7)$$

We will get:

$$v_{xn} = \frac{a_{wn}}{m_n+1} [y_0^{m_n+1} (h_n - y_0)^{m_n+1}] \quad (8)$$

To illustrate the nature of the movement of the pressed material in the screw channel, velocity plots are constructed according to the previously obtained solution of equations (3) and (5) dependences [1], [5]:

$$v_{x1} = v_{xn} + \frac{a_w}{m+1} [(y_0 - y)^{m+1} - y_0^{m+1}] \quad (9)$$

$$v_{x2} = v_c + \frac{a_w}{m+1} [(h_w - y_0)^{m+1} - (y - y_0)^{m+1}] \quad (10)$$

If $h_n < y_0 < h_w$, using the boundary condition $v_{x1} = v_{x2}$ at $y = y_0$ it is possible to determine from equations (9) and (10) the value y_0 , given the velocity v_c of the upper plate (see Figure 1), or to determine the value necessary for this velocity distribution v_c , given the value y_0 . If $y < h_n$, similar solutions can be obtained from equations (9) and (7) or (9) and (8) using the boundary $v_n = v_{x2}$ condition at $y = h_n$.

As a result of experimental studies conducted by [13], [14], it was found that the assumption about the origin of the slip layer due to local heating of the material is not confirmed, since in this case there is no noticeable slippage along the bottom of the screw channel.

As a result, the authors of the experiment explain the occurrence of a boundary layer with rheological parameters different from the parameters of the main material in the screw channel, which consists of the distribution of the power of the layered flow in the material.

Thus, the equation of the specific power of the layered flow of the magnitude will take the following form [7], [9].

$$N_U = \tau_{xy}(v_{xi} - v_c), i = 1,2 \quad (11)$$

Where:

τ_{xy} – shear stress in compressed material.

Formula (11) considers that the pressed material's speed was considered higher in the reversed movement of the screw pressing mechanism. The velocity is determined by equations (9) and (10). Taking into account equation (2), formula (11) is transformed to the form (12): [7], [9]:

$$N_U = \frac{d\sigma}{dx} (y - y_0)(v_{xi} - v_c) \quad (12)$$

Where:

$\frac{d\sigma}{dx}$ – the gradient of normal stresses in the compressed material; y_0 – the coordinate of the plane on which shear stresses take place.

$$\tau_{xy} = 0$$

The study of the casts of the pressed material extracted from the screw channel suggests that the thickness of the boundary layer can be neglected compared to the height of the screw channel h_n . Therefore, when determining the flow of material in the channel h_{uu} , the flow in the boundary layer can be neglected [1], [19].

The above theoretical prerequisites formed the basis for calculating and optimizing the main technological indicators of the process of extrusion of bulk components for the production of products with a high degree of readiness [16], [17], [18].

Following the planning of the multifactorial experiment, Table 1 was compiled. A list of variable factors was determined, and their variation intervals and levels were established. The degree of influence of the values of the selected factors on the criteria for optimizing the process of extrusion of a loose poly-cereal mixture is calculated. The criterion for optimizing the extrusion process is the energy value of «Fitness» and «Health» of high-readiness products [16], [17], [22], [23].

Table 1 Experimental values of variable factors and optimization criteria according to the planning matrix.

Natural values		Experimental values of technological parameters and criteria for optimizing the extrusion process					
W, %	n, rpm	P, MPa	t, °C	Q, kg/h	N, kW	E _v , kcal	
						Poly-cereal product «Fitness»	Poly-cereal product «Health»
1	2	3	4	5	6	7	8
3.5	120	18.25	152.7	210	44	314.52	316.68
3.5	210	21.05	212.6	370	76.5	322.38	324.54
16.5	120	14.45	151.9	205	41.0	314.40	316.70
16.5	210	20.95	211.6	365	73.0	321.20	323.50
12.0	170	17.88	183.3	295	64.5	316.01	318.30
18.0	170	17.75	181.9	280	56.0	315.45	320.60
15	80	12.0	130.0	144	28.8	313.85	315.60
15	250	25.0	250.0	450	90.0	332.34	334.09
15	170	18.48	189.4	306	61.2	317.50	319.25

High-readiness poly-cereal products «Fitness» and «Health» are shown in Figure 2. They differ only in the composition of the poly-cereal mixture from which they are made [16], [17].

**Figure 2** High-readiness poly-cereal products a) «Fitness» and b) «Health».

The results of experimental studies were entered into a table of a *Microsoft Excel* word processor, and then, based on the data obtained, three-dimensional graphs of the dependence of the pressure created in the pre-matrix zone (P , MPa), the temperature of the finished product at the exit from the working zone (t , °C), the productivity of the extruder (Q , kg/h), the power consumption of the electric drive during the extrusion process (N , kW h), the energy value of high-readiness products «Fitness» and «Health» (E_v , kcal) on variable values of the rotation speed of the extruder screw n , (min^{-1}) and humidity of the extruded poly-cereal mixture, W (%) [17], [20].

Analysis of the experimental data presented in Table 1 showed that an increase in the rotation speed of the working organ n from 80 to 250 min^{-1} leads to an increase in the pressure values in the pre-matrix zone. At the same time, the humidity of the processed flour poly-cereal mixture reduces during the extrusion process.

In addition, an increase in the rotation speed of the working body (screw) n from 80 to 250 min^{-1} leads to an increase in the temperature of the extrudate at the outlet of the working area of the device (t , °C). And the humidity of the extruded flour multicomponent mixture changes the temperature values during the extrusion process.

It was also observed that an increase in humidity up to 15% led to an increase in t values up to 130 °C. A further increase in humidity to 18% reduced the temperature of the extrudate at the exit from the working area of the device.

It has been experimentally established that an increase in the rotation speed of the working body (screw) n from 80 to 250 min^{-1} increases the productivity of a twin-screw extruder (Q , kg /hour). At the same time, the humidity of the processed flour poly-cereal mixture changes the Q values during the extrusion process.

And also, an increase in the rotation speed of the working body (screw) n from 80 to 250 min^{-1} leads to an increase in the power consumption of the electric drive of the extruder (N , kW/hour). At the same time, the humidity of the processed flour poly-cereal mixture reduces the N values during the extrusion process.

Experimental data indicate that an increase in the rotation frequency of the working organ (screw) n from 80 to 250 min^{-1} leads to the most significant increase in the energy value of a poly-cereal food product of a high degree of readiness (E_v , kcal), respectively, for «Fitness» 332.34 kcal and for «Health» - 334.09 kcal. At the same time, the humidity of the processed flour poly-cereal mixture slightly changed the E_v values during the extrusion process [16], [17].

Thus, the analysis of the experimental data is presented in Table. 1 showed that an increase in the speed of rotation of the working body n from 80 to 250 min^{-1} leads to an increase in the pressure values in the pre-matrix zone. This also increases the temperature of the extrudate at the exit from the working area of the device; the productivity of a twin screw extruder, and the power consumption of the extruder electric drive. An increase in the moisture content W of the polycereal flour mixture from 15% to 18% reduces the pressure values in the pre-matrix zone; extrudate temperature during extrusion; productivity, and power of the electric drive of a twin-screw extruder.

An analysis of the experimental data also indicates that an increase in the speed of rotation of the working body (screw) n from 80 to 250 min^{-1} leads to the largest increase in the energy value of a highly prepared poly-cereal food product, respectively, for "Fitness" 332.34 kcal and for "Health" - 334.09 kcal. At the same time, the influence of moisture content W of the processed poly-cereal flour mixture on the energy value of the finished product is insignificant.

An analysis of the obtained three-dimensional surfaces of extruded products showed that the performance characteristics of the extruder at all values of the screw speed are the same, i.e. the extruder first increases and then decreases from a certain value of Q . It is obvious that in the completely closed exit mode at $Q = 0$, the pressure in pre-matrix zone continuously increases, and in the open output mode $Q = Q_{max}$ – continuously decreases. In a real extrusion process, with increasing productivity, the pressure of the product reaches a certain value, the maximum possible for the given operating conditions of the extruder, and then steadily decreases [16], [21], [24].

As a result of the analysis, the influence of the factors taken into account on the temperature and pressure of the food medium has been experimentally confirmed: the design parameters of the extruder (the diameter of the through a section of the matrix), as well as the initial humidity of the mixture, have the greatest influence on the melt pressure of the product; the geometric characteristics of the working body, the frequency (speed) of the screw rotation and the pressure of the product maximally affect the temperature in the pre-matrix zone of the extruder. They allow us to find out the dominant value of each studied factor (W , n) on kinetic parameters and describe with a sufficient approximation the kinetics of the extrusion process of flour poly-cereal mixture in the production of high-readiness products «Fitness» and «Health».

CONCLUSION

The developed theoretical premise made it possible to calculate and optimize the main technological parameters of the extrusion process of bulk components for the production of high-readiness products «Fitness» and «Health». Experimental data indicate that an increase in the rotation frequency of the working organ (screw) n from 80 to 250 min^{-1} leads to the greatest increase in the energy value of a poly-cereal food product of a high degree of readiness (E_v , kcal), respectively, for Fitness product 332.34 kcal and for Health product - 334.09 kcal. The influence of the factors taken into account on the temperature and pressure of the food medium has been experimentally confirmed: the design parameters of the extruder (the diameter of the cross-section of the matrix), as well as the initial humidity of the mixture, have the greatest influence on the melt pressure of the product; the geometric characteristics of the working body, the frequency (speed) of the screw rotation and the pressure of the product maximally affect the temperature in the pre-matrix zone of the extruder. They allow us to find out the dominant value of each studied factor (W , n) on kinetic parameters and describe with a sufficient approximation the kinetics of the extrusion process of flour poly-cereal mixture in the production of high-readiness products Fitness and Health.

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