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Potravinarstvo Slovak Journal of Food Sciences

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Slovak Journal of Food Sciences

Potravinarstvo Slovak Journal of Food Sciences
vol. 14, p. 937-944
https://doi.org/10.5219/1436
Received: 14 July 2020. Accepted: 26 September 2020.
Available online: 28 October 2020 at www.potravinarstvo.com

ISSN 1337-0960 (online)

MATHEMATICAL MODELING OF THE OIL EXTRUSION PROCESS WITH PRE-GRINDING OF RAW MATERIALS IN A TWIN-SCREW EXTRUDER

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ABSTRACT

The extrusion process of oil-containing raw materials using a twin-screw extruder is becoming increasingly common in food technology. The problem of high energy costs for the implementation of this process is solved by reducing the resistance of the process mass due to the preliminary grinding of raw materials. The classical theory of extrusion is based mainly on the use of theoretical solutions of mathematical models of processes, which are simplified and allow determining integral parameters using coefficients, the preparation of which for the calculation of the corresponding processes and equipment is a rather complicated and approximate procedure. Mathematical modelling of the movement of the technological medium at the individual stages of the processing of raw materials allows us to determine the analytical dependences for the power and energy parameters of the system and to carry out their effective technical and economic evaluation. Using the methods of mathematical analysis and data processing in the MathCAD software environment, graphical dependences of the power and energy parameters of the research technical system were obtained. By increasing the density of the oil-containing raw materials, which is extruded in the research extruder by 40.5% the pressure force increases by 41%, that is, there is an almost proportional relationship between the pressure force and the density of the processed raw material. With an increase in the angular velocity of the drive shaft ω more than 8 rad.s^{-1}, the pressure force in the research process increases sharply. With an increase in the density of raw materials, it is grinded before extrusion by 40%, the power consumption for the grinding process increases by 2.8 times for the recommended operating mode. Energy losses for pressing completely grinded raw materials are reduced by 2.52 times.

Keywords: process; extrusion; oil-containing; raw materials; energy consumption; extruder

INTRODUCTION

The theory of extrusion was developed mainly for the case of processing synthetic materials, which throughout the volume have a relatively uniform molecular weight and are characterized by a high level of dissipation of mechanical energy **(Shi et al., 2019)**. In the overwhelming majority of works on modelling the single-screw extrusion process, the inverse screw model is considered, which allows us to reduce the problem to a rectangular coordinate system, considering the screw to be stationary and unfolded on the plane, and the working cylinder to be moving relative to the screw and also unfolded on the plane **(Martin and Otakar, 2017)**. The classical theory of extrusion is based on the use of theoretical solutions of mathematical models of processes, which are simplified and allow us to determine, basically, integral parameters. In a significant part of the work, coefficients are introduced, the obtaining of which is rather difficult to calculate the corresponding processes and equipment **(Kudrin, 1997)**. The use of computer technology allows us to analyse more complex models, which make it possible to assess the influence of several factors on the extrusion process, but in many cases, it does not lead to significant refinement of the results, it requires the selection of factors that most significantly affect the extrusion process and satisfy the requirements of designers **(Herman, 1975)**. Many researches are devoted to the research of viscous-plastic mass flows along a conical channel, in cylindrical pipes, in channels of a rectangular, square, elliptical, screw, and complex section. In some works, the movement of viscoplastic food materials was analysed based on ideas about the dosing zone, and the effect of wall sliding was estimated **(Petrov and Slavnov, 2013)**. The research twin-screw press extruders are distinguished by longer helical shafts, due to the introduction of special mixing and grinding elements in their designs. In scientific works **(Palamarchuk et al., 2020; Zeleňáková et al., 2019; Shahbaz et al., 2017)**, based on researches conducted under industrial conditions, a dosing zone is described based on hydrodynamic analysis of flows within individual C-shaped volumes **(Sheiko et al., 2019)**. The leakage flows through gaps, compression of raw materials, the distribution of pressure in the channel and the influence of these factors on the performance of the extruder as a whole are considered. In many scientific works **(Mushtruk et al., 2020; Tsagareishvili et al., 2019; Zheplinska et al., 2019)** the rheology of the behavior of raw materials is described in sufficient detail, formulas are given for the design calculation of twin-screw extruders, and the effect of mixing and crushing working bodies of twin-screw extruders on the processing of rubber compounds and plastics is described. Effective mathematical modelling of twin-screw extruders has long been limited to the development of geometric parameters and the justification of processing modes, based on practical experience and experimental data, due to the rather complicated design of the executive bodies **(Pugachev, Levina and Shalaeva, 2011)**.

The aim of this scientific work is a feasibility study of the implementation of the stage of preliminary grinding of oil-containing raw materials in the extrusion process of oil by a twin-screw extruder based on a theoretical graph-analytical analysis of the power and energy parameters of the process. To achieve this aim it is necessary to solve the following tasks:

- determination and assessment of power and energy characteristics for the implementation of the mechanical extrusion of the liquid fraction of oil-containing raw materials;
- obtaining graphical interdependencies of the research factors for the developed extruder circuit;
- substantiation of regime power and kinematic parameters of the executive bodies of the developed extruder.

Thus, the theoretical justification of the power and energy parameters during the implementation of individual stages of the extrusion process of oil-containing raw materials to reduce energy consumption and increase oil yield is quite an urgent task, which is solved in this scientific research.

Scientific hypothesis

Grinding of oil-containing raw materials before pressing and selection of the optimal operating mode of the extruder can increase the efficiency of its operation – increase the pressing force and oil yield and reduce energy consumption for the process.

MATERIAL AND METHODOLOGY

When operating screw presses, from the beginning to the end of the pressing of seeds, it passes from one physical state to another until the oil and oil meal come out. To research these processes, they used the method of separation or decomposition, examining them in stages. Although the individual stages are interconnected, each of them in a complex system of processing of raw materials can occur simultaneously, parallel or sequentially, which happens inside the extruder's press path, where the operations of transportation, grinding, mixing, heating and extrusion of the raw material are carried out.

When conducting a theoretical analysis and justification of the power, torque and energy characteristics of the developed twin-screw apparatus for oil extrusion, methods of mathematical analysis and data processing in the MathCAD software environment were used to obtain the necessary graphical and analytical dependencies describing the main operating parameters of the system.

Statistical analysis

The statistical evaluation of the results was carried out by standard methods using statistical software Statgraphics Centurion XVII (StatPoint, USA) – multifactor analysis of variance (MANOVA), LSD test. Statistical processing was performed in Microsoft Excel 2016 in combination with XLSTAT. Values were estimated using mean and standard deviations.

RESULTS AND DISCUSSION

In scientific works **(Kehinde, 2016; Sokolov et al., 2018)** various schemes of the process of reception of oils from seeds of various oil-containing cultures which have several lacks are presented **(Palamarchuk et al., 2019; Prashanth et al., 2019)**. The general scheme of the process of obtaining oil from seeds of oil-containing crops in a twin-screw press extruder (Figure 1) can be described as follows. A raw material (seeds of oil-containing cultures) through the neck of the hopper *1* by gravity are sent to the loading chamber of the extruder and fills the free space between the inner wall of the chamber and screw turns. The seeds are captured by the coils of the screw nozzles *2* and are moved to the heating chamber *3*, where it is gradually compressed, and in the area of the cam nozzles *4* is partially grinded and heated from the walls of the chamber. Then the raw material enters the grain chamber *5*, where it is pressed. Part of the oil flows through the grain of the hole, and the remaining raw materials are transported to the next extraction zone – heating chambers and extrusion. Screw nozzles along with the shaft alternate with grinding. To increase the yield of oil, pressing occurs in several stages with their repetition in the extrusion path. In the area of the cone nozzles *6* and matrix *7*, the oil meal is removed from the extruder in the form of petals or granules.

When describing the screw pressing mechanism, the principle of dividing it into sections is applied. In scientific works **(Polosin and Chistyakova, 2014; Shirazian et al., 2017; Chen et al., 2019)** this principle of division into sections was not used. A section can end with a matrix or a compression shutter – a section of the mechanism on which the screw turn is interrupted and the passage section of the extrusion path of the extruder is reduced **(Owolarafe, Osunleke and Odejobi, 2008)**.

In accordance with the specified method of separation into sections or elementary screw mechanisms with conditionally constant parameters of the pressing process, the press path of the research twin-screw press extruder was divided into four conditional sections: I, II, III, and IV. Each section ends with a section of the mechanism on which the bore of the extrusion path of the press is reduced or increased within the same type of working bodies. In section *I* there is a displacement of the material in the auger channel, in section *II* there is a partial grinding of production in the area of the triangular cam nozzles and the movement of the raw material in the compression gate, in section *III* – the extrusion of oil through the holes in the grain chambers, and ie section *IV* – the displacement of the material in the matrix.

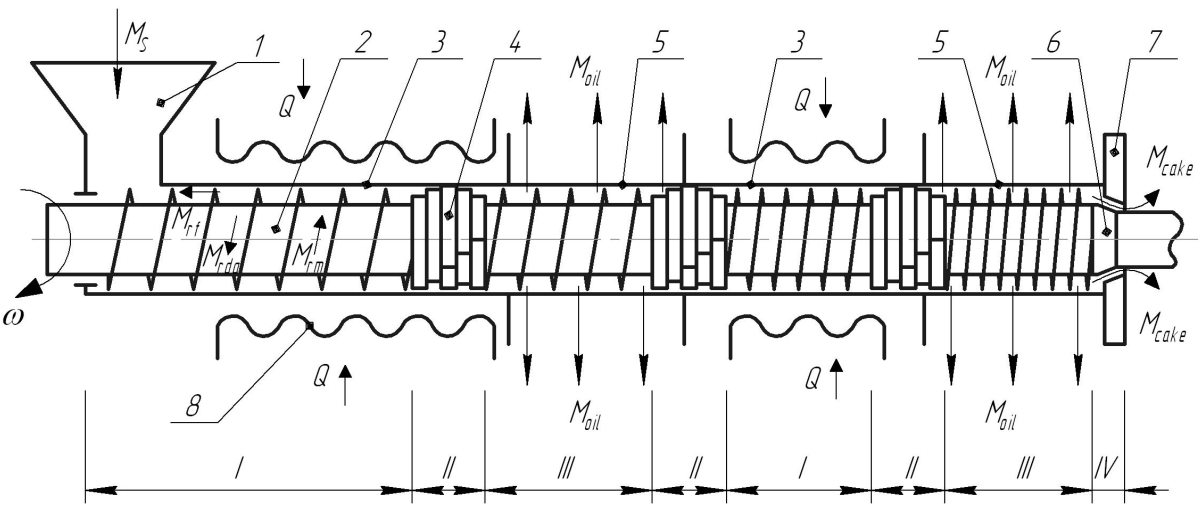


Figure 1 The design scheme of a twin-screw press extruder. Note: 1 – hopper, 2 – twin screw, 3 – heating chamber, 4 – grinding elements (nozzles), 5 – grain chamber, 6 – cone nozzle, 7 – matrix, 8 – electrical heating. Note: M_s – a mass of seeds; *Q* – the amount of heat supplied to the raw material; M_{rm} – a mass of the main flow of raw materials; M_{oil} – a mass of the pressed oil; M_c – a mass of oil cake; M_{rf} *a* – mass of the return flow of raw material directed along the gap between the cylinder and the screw; M_{rda} a – mass of the return flow of raw material directed along the channel of the profile of the auger.

Assuming that in the research process grinding of seeds is realized in the radial direction to the center of the seeds, it is possible to determine the geometric parameters of the grinding unit of the extruder, which are presented in Figure 2.

Using the calculated scheme of the interaction of the cams (Figure 3) we obtained that, $\sin\frac{\alpha}{2} = 0{,}5\sqrt{\frac{d_s}{r_{ge}}}$

In the research system, three main forces can be noted: grinding force F_P; a force of pressure created in the screws of the screw F_S; friction force F_f. The direction of the grinding force is taken normal to the seed, which is crushed (Figure 2). In scientific works **(Bako, Enyi, and Imolemhe, 2020; Soares, Zhang and Sacks, 2017)** the force of pressure created in the screws of the auger and the force of friction was determined, and in scientific works **(Bogaert et al., 2018; Tuta and Palazoğlu, 2017; Herak, 2013)** the force of friction and the force of demand were determined.

Given the regularities of the mechanics of movement of the executive bodies and the geometric characteristics of the extruder presented above (Figure 2), we write the expression for the projection of the pressure force on the *ox* axis in the form:

$$F_x = 0.393 n_S (D_S^2 - d_S^2) P_{max} = 3.75\omega (D_S^2 - d_S^2) P_{max} \qquad (1)$$

Where: n_S and ω – respectively, the speed and angular velocity of the screw shaft; D_S – the outer diameter of the screw auger; d_S – the outer diameter of the auger body; P_{max} – the maximum pressure that develops the auger.

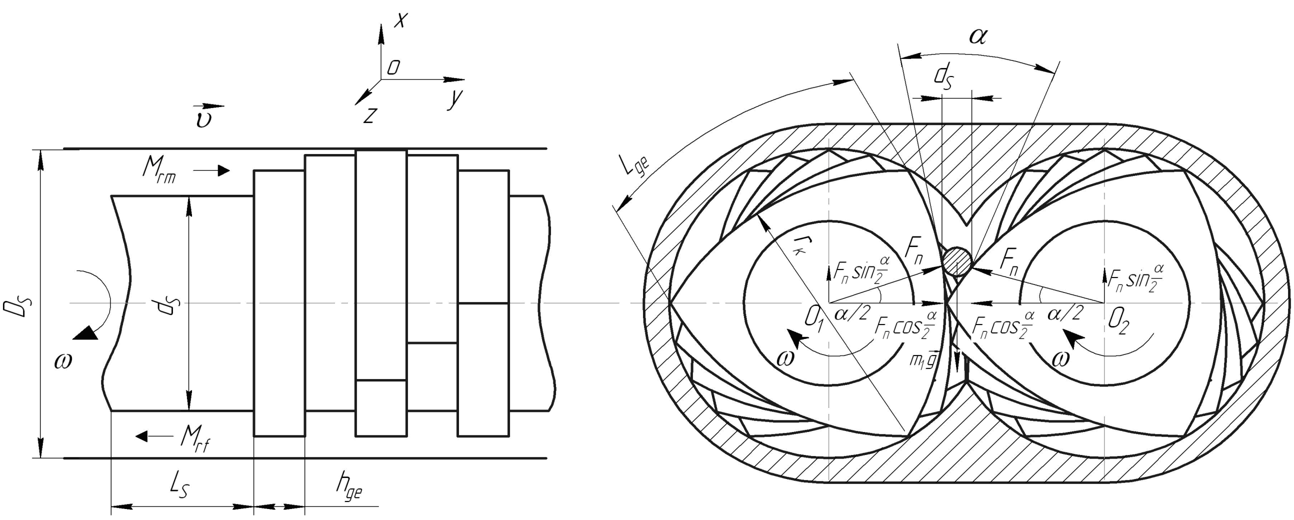


Figure 2 Scheme for determining the geometrical parameters of the seed grinding unit in triangular cam nozzles. Note: D_S – the outer diameter of the screw coil, d_S – the outer diameter of the screw body, L_S – the length of the screw nozzle, L_{ge} – the width of the cam nozzle, L_{ge} – the width of the cam nozzle length of cam nozzle, O_1, O_2 – centers of cams; r_{ge} – the radius of the cam; d_s – diameter of the seed, ω – the angular velocity of the shaft.

The friction force of raw materials on the inner surface of the extruder body can be described by the formula:

$$F_f = k \cdot F_d \cdot F_{ad} \quad (2)$$

Where: k_f – the coefficient of friction of the raw material on the inner surface of the housing; F_d – a force of deformation of raw materials: $F_d = F_x$; F_{ad} – adhesive force, which takes into account the adhesion of the product with the parts of the press is determined by the adhesive experimentally.

The projections of the momentum of the elements of the system under study along the coordinate axes are:

$$m_1\upsilon_z = \left(F_S - F_S \cdot k_t - F_{ad}\right)t_1 \quad (3)$$

Where: m_1 – the mass of raw material;

$$m_1\upsilon_x = \left(2F_P \sin\frac{\alpha}{2} + F_x - F_x \cdot k_t - m_1 g - F_{ad}\right)t_2 \quad (4)$$

It is obvious that $m_1\upsilon_y = 0$

The axial velocity of the raw material along the auger channel can be determined by the formula

$$m_1\upsilon_x = \left(2F_P \sin\frac{\alpha}{2} + F_x - F_x \cdot k_t - m_1 g - F_{ad}\right)t_2 \quad (5)$$

$$\upsilon_z = \frac{z \cdot n_S}{60} = \frac{z \cdot \omega}{2\pi}$$

The time of promotion of products to the section with grinding cams is $t_1 = \frac{z}{\upsilon_z}$, and at $z_{max} = L_S$ that time will increase to $t_1 = \frac{L_S}{\upsilon_z}$. The grinding time of products between the surfaces of the cams is $t_2 = \frac{x}{\upsilon_x}$, and at $x_{max} = L_{ge}$ this time is calculated as follows $t_2 = \frac{L_{ge}}{\upsilon_x}$.

Using the presented equations, the projections of the mass forces of a mechanical system on the coordinate axis can be represented as:

$$F_z = \frac{(F_S(1-k_t) - F_{ad})}{m_1} = \frac{\upsilon_z}{t_1} = \frac{\upsilon_z^2}{z} \quad (6)$$

Where: z – the current coordinate.

$$F_x = \frac{(2F_P \sin\frac{\alpha}{2} + F_x(1-k_t) - m_1 g - F_{ad})}{m_1} = \frac{\upsilon_x}{t_2} = \frac{\upsilon_x^2}{x} \quad (7)$$

Where: x – the current coordinate; g – the acceleration of gravity.

Obviously a component $F_y = 0$

Based on the developed calculation scheme of the grinding unit, efforts were found to grind the raw materials from the equation of conservation of the amount of its movement.

$$m_1\upsilon_x = \left(2F_P \sin\frac{\alpha}{2} + \frac{P_x}{S}\left(1-k_r\right) - m_1 g - F_{ad}\right)\frac{L_{ge}}{\upsilon_x} \quad (8)$$

Then the grinding force can be found by the equation:

$$F_P = \frac{1}{2\sin\frac{\alpha}{2}}\left[\begin{array}{l}\frac{m_1\omega^2 r_{ge}{}^2}{L_{ge}} - \frac{\omega^2 r_{ge}{}^2 \rho \ln L_K}{L_{ge} z_{ge} h_{ge}}\left(1-k_t\right) + \\ + m_1 g + F_{ad}\end{array}\right] \quad (9)$$

or

$$F_P = \frac{1}{2\sin\frac{\alpha}{2}}\left[\begin{array}{l}\frac{\omega^2 r_{ge}{}^2}{L_{ge}}\left(m_1 - \frac{\rho \ln L_{ge}}{z_{ge} h_{ge}}\right)\left(1-k_t\right) + \\ + m_1 g + F_{ad}\end{array}\right] \quad (10)$$

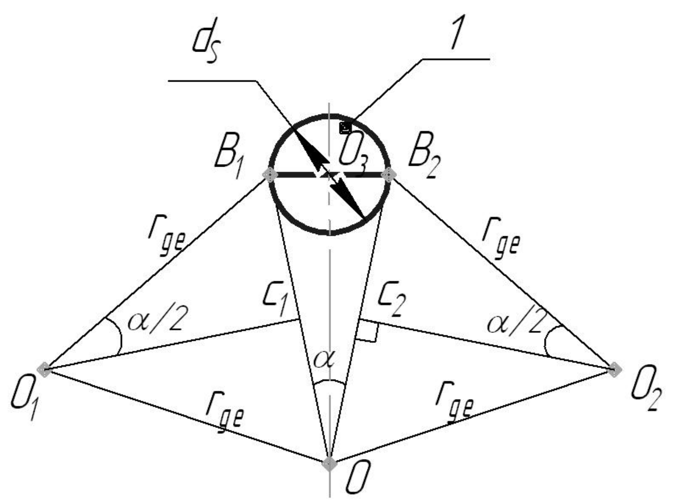


Figure 3 Settlement scheme of interaction of grinding cams. Note: *1* – seed; O_1, O_2 – the centers of the cams (grinding elements); r_{ge} – the radius of the cam (grinding elements); O_3 – the center of the seed; d_s – the diameter of the seed.

Based on the obtained equations and using the MathCAD software environment, graphical dependences for the force and power characteristics of the research process were obtained (Figure 4), of which it is evident that with increasing the density of the extruded slurry by 40.5%, the pressure force increases by 41%, i.e. there is a proportional relationship between the pressure force and the density of the raw material processed. In work **(Anderegg et al., 2019)** was installed the pressure force increases by 31%, in the work **(Troshin, 2017)** was installed the pressure force increases by 34.2%, in the work **(Leray, et al., 2016)** was installed the pressure force increases by 24.2%. With an increase in the angular velocity of the drive shaft ω more than 8 rad.s^{-1}, the pressure force on the raw material increases sharply, which justifies the recommended angular speed of rotation of the extruder shaft in the range ω = 4 – 7 rad.s^{-1}. The authors of the following scientific works **(Yang et al., 2018; Zhou et al., 2019)** recommend the angular velocity of rotation of the extruder shaft in the range ω = 8 – 12 rad.s^{-1}, but rational is the speed not exceeding 7 rad.s^{-1}. For the recommended regime of rotational movement of the extruder's executive bodies, the force of grinding products by working rolls F_p increases 3 times (Figure 4, a) during the extraction of raw materials, the density of which increases by 40%. Moreover, this force varies within 1.5 – 6 kH. The authors of the following scientific works **(Syryamkin et al., 2019; Kolyanovska et al., 2019)** investigated that the grinding force ranges from 5.5 to 16 kN.

With an increase in the density of raw materials, it is grinded before being extruded by 40%, the power consumption for the grinding process increases by 2.8 times and amounts to 0.7 – 2 kW for the recommended operating mode (Figure 4, b). In scientific works **(Cai and Liu, 2017; Mamanpush et al., 2018)** it is proved that with an increase in the density of raw materials, it is grinded before being extruded by 30%, the power consumption for the grinding process increases by 0.8 – 1.2 times and amounts to 0.1 – 0.8 kW **(Cherednichenko and Bal-Prylypko, 2019; Zheplinska et al, 2020)**.

To evaluate the effectiveness of preliminary grinding of seeds in the process of oil extrusion, the following calculation procedure was used **(Iuga et al., 2016)**, according to which the pressure is determined by the formula:

$$P = c \cdot \rho^{m}, Pa \tag{11}$$

For whole seeds c = 1.76·10^{-3}, m = 6.66, that is P_0=1.76·10^{-3}·$\rho_0^{6.66}$, and for grinded seeds c = 3.3×10^{-32}, m = 11.84, that is P_1=3.3·10^{-32}·$\rho_1^{11,84}$

Where: ρ_0 – density of whole seeds, ρ_0 = 1000 – 1050 kg.m^{-3}; ρ_1 – density of grinded seeds, ρ_1 = 1110 – 1150 kg.m^{-3}.

The ratio of the power consumption for pressing whole seeds N_0 and grinded N_1 is:

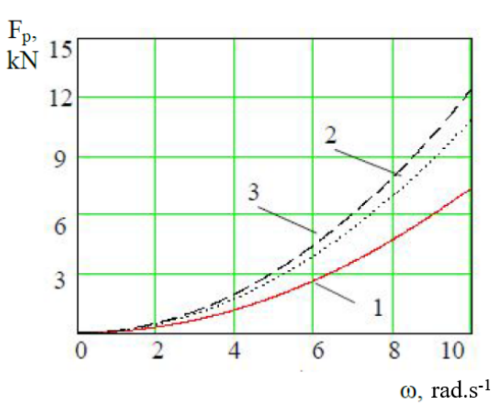
$$k_N = \frac{N_0}{N_1} = \frac{P_0}{P_1} = \frac{1.76 \cdot 10^{-13} \cdot \rho_0^{6.66}}{3.3 \cdot 10^{-32} \cdot \rho_1^{11.84}} = 294 \tag{12}$$

When the energy efficiency coefficient k_N was introduced to evaluate the research process, it was found that the coefficient c is inaccurate for the grinded material. After clarification for the grinded raw materials c = 3.86×10^{-30}.

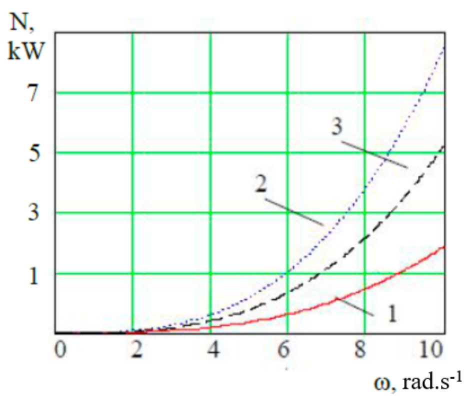
Then $k_N = \frac{N_0}{N_1} = \frac{P_0}{P_1} = 2.52$

That is, the energy loss for pressing the grinded material for the research process of oil extrusion is reduced by 2.52 times. The rational design and technological parameters of the modernized press extruder were determined based on the experimental researches, which were: the temperature of the first and second heating zones of the buildings 115 – 130 °C, the gap in the matrix 0.0042 – 0.005 m, the angular speed of the screw shaft 4 – 7 rad.s^{-1}, the time of technological influence on the oil-containing material in the tract of the press is 45 – 75 s.

Application of new working bodies allows to increase the productivity of the machine and to reduce energy consumption for the process of oil extraction. The theoretical compression ratio of a press extruder with a set of new working bodies for the processing of sunflower, rapeseed and soybean seeds is 4.69; 3.36 and 2.55. This ensured the intermediate compaction of the oil-containing raw material, the intensification of its crushing, and the increase of oil yield to 3%.



a)



b)

Figure 4 Dependences of the force of grinding of raw materials by working cams F_P (a) and the cost of power when grinding products by working cams N (b) of the angular velocity of the drive shaft ω during the extrusion of oil from seeds. Note: 1 – sunflower (ρ = 440 kg.m^{-3}); 2 – rapeseed (ρ = 650 kg.m^{-3}); 3 – soybeans (ρ = 740 kg.m^{-3}).

CONCLUSION

1. Based on mathematical analysis of the movement of raw materials at separate stages of the extrusion process of oil in the developed twin-screw extruder determined the power and energy parameters of the research process and proved that the energy losses under the conditions of pre-grinding of seeds and, accordingly, reduction of technological resistance of the dispersed medium during oil extrusion are reduced by 2.52 times.
2. The graphical dependencies obtained in the MathCAD computer software environment showed that with an increase in the density of raw materials, it is grinded before being extruded by 40%, the power consumption for the extrusion process increases by 2.8 times and amounts to 0.7 – 2 kW for the recommended operating mode of the extruder.
3. For the recommended angular velocity of the extruder actuators (ω = 4 – 7 rad.s^{-1}), the grinding force of the raw materials by the work rolls F_p increases by 3 times.

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