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STUDY OF REGULATIONS OF PRE-EXTRUSION PREPARATION OF CASTOR OIL RAW MATERIAL AND ITS EFFECT ON PRESSING

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The results of studies of the effect of preliminary extrusion preparation of castor seeds on the parameters of the pressing process and the quality of the obtained oil are presented. Based on the analysis of thermophysical processes, a five-zone model of extruder temperature regimes is proposed, taking into account heat exchange, mass exchange and individual characteristics of raw materials, an observer model is derived for estimating the output of the target product

Based on the regression model, the change in pressure in the pre-matrix zone of a single-screw extruder is described, depending on the moisture content of the raw material, the rotation frequency of the screw, and the diameter of the forming channel of the matrix. The experimental dependences of the product temperature on the drive power and productivity for different humidity are summarized, and the interpretation of the response surfaces obtained is presented.

The proposed combined model apparatus allows overcoming the limitations of existing control systems, in addition, the observer model provides the possibility of implementing adaptive control algorithms, as well as the optimization of extrusion parameters allows to increase oil output by 12-15% and improve its quality characteristics.

The obtained results provide a scientific basis for the development of intelligent control systems for extrusion–pressing processes of castor oil production, oriented toward variable raw material properties and energy constraints of equipment. The proposed approach integrates physically grounded thermophysical models with empirical regression dependencies, enabling real-time prediction of technological parameters and formation of control actions based on the criterion of maximizing oil yield while preserving its quality characteristics. The practical value of the study lies in the possibility of using the developed modeling framework in the design and modernization of press–extruders for oilseed processing, as well as in the implementation of adaptive control algorithms that ensure improved energy efficiency of the process and stability of product parameters under conditions of varying moisture content and fractional composition of seeds.

Key words: *press-extruder, castor oil, thermophysical model, observer model, pressure regression model, adaptive control, oil yield, oil quality.*

Eq. 4. Fig. 3. Ref. 17.

1. Problem formulation

Oilseed crops play a key role in the national economy, as they serve as a source for the production of high-value food and industrial products. Among these crops, castor bean (*Ricinus communis*) occupies a special place. The main product of its processing is castor oil, whose content in the seeds reaches 50–55%. In combination with its unique chemical composition, dominated by glycerides of ricinoleic acid (81–96%), this makes castor oil an indispensable raw material for a number of critically important industries, including the

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military, chemical, mechanical engineering, and medical sectors, which determines its status as a strategic resource [1].

The screw press is the main unit for castor oil extraction; however, its traditional design and operating modes do not always ensure maximum efficiency. The pressing process is based on pressure generation through volumetric deformation of the mash, which is achieved by changing the geometry of the press working elements. Nevertheless, without preliminary intensifying treatment of the raw material, this method has certain limitations, namely a relatively low total oil yield (high residual oil content in the cake) and significant energy consumption, which necessitates the search for ways to optimize the entire technological chain [2].

Therefore, to obtain high-quality oil, it is important to reduce thermal loads and the residence time of raw material at elevated temperatures, while simultaneously ensuring sufficient destruction of the cellular structure before it enters the press to enable efficient oil release. Preliminary extrusion treatment combines short-term high-temperature exposure with intensive mechanical deformation, which promotes cell disintegration and reduces anti-nutritional factors.

2. Analysis of recent research and publications

Modern equipment for pressing oilseed crops, particularly sunflower, demonstrates insufficient efficiency when processing castor seeds. Existing technologies do not ensure complete oil extraction from the mash or achievement of a minimal residual oil content in the cake. As a result, the technological process of castor oil production requires the introduction of additional or repeated operations, which complicates and increases the cost of production [3].

The key raw material is castor seed, whose oil content reaches 55%, while the husk content does not exceed 11% [4]. At the first stage of processing, the seeds are crushed into meal, which is then treated with moisture and heat to obtain a wax-like mash. This mash is subsequently directed to preliminary pressing. A regulated quality indicator for the resulting cake is its residual oil content, which should not exceed 8.5% [5].

The formation of an optimal structure of castor seed mash is a key factor in improving castor oil production technology, since this parameter directly determines the quality characteristics of the final product [6].

The duration of the compaction process is determined by the geometry of its zone and the physicomechanical properties of the interacting phases of the mash [7]. The mechanism of this process consists in the gradual extrusion of castor oil with dissolved components, accompanied by rheological transformations in its gel-like hydrophilic phase [8].

The formation of the mechanical properties of the mash depends on the presence of the gel phase and the degree of oil release, while its physical behavior is an integral indicator of the properties of both components. As a result, the compaction process has a dual nature: on the one hand, a temporary volumetric change of the gel phase occurs due to deformation of its viscous structure; on the other hand, mutual displacement of the oil and gel phases takes place [9].

A review of scientific sources indicates the existence of two key technological solutions in preparing castor seeds for oil extraction. As noted in [10], the main criterion is the division into processes with preliminary dehulling and without it. According to [11], the first option is more complex and includes stages of cracking, separation, kernel grinding, and moisture–thermal treatment. The second, simplified option involves only seed grinding and mash preparation, which significantly reduces process complexity.

According to the literature [12], the distribution of key components in castor seeds is of fundamental importance for oil quality. Useful components such as proteins and lipids are localized mainly in the kernel, whereas the husk contains high concentrations of undesirable compounds. Among them is the toxic alkaloid ricinine, which, when transferred into the oil, significantly deteriorates its quality. In addition, the shell is a source of nitrogen-free substances, oxidation products, fatty acids, waxes, and coloring pigments, the presence of which reduces oil transparency and marketability.

Studies by other authors [13–15] indicate that preliminary extrusion treatment of oil-bearing raw materials prior to pressing reduces the content of anti-nutritional compounds, stabilizes the acid value, facilitates refining, and can increase oil yield. At the same time, the quantitative role of the controlled parameters W, ω, d_M in the formation of pressure and temperature in the pre-die zone requires modeling and verification on experimental installations.

3. The purpose of the article

The aim of the study is to present the regularities of the process in a systematic form, to describe their models, and to confirm the improvement of oil quality due to extrusion treatment.

The objectives of this work are: (I) to develop a regression model for pressure $P(W, \omega, d_M)$; (II) to generalize the dependencies $T(N, Q;\ W)$; and (III) to compare the technological and quality indicators of oil before and after extrusion.

4. Results and discussion

1. Thermophysical model of the castor oil press extrusion process.

To increase the yield of vegetable oil in press–extruders, an adaptive control system has been implemented that uses the temperatures in the heating zones as control actions. However, a key drawback of this approach is the high inertia of the temperature regimes. The time required for the temperature to reach the заданий (set) level amounts to tens of minutes, which significantly limits the flexibility of the unit. As a result, a five-zone press–extruder with a capacity of 800 kg per shift equipped with such a system is effective only when processing large batches of raw material. When operating with small batches (for example, under tolling schemes), the inequality that determines process stability is violated. During the processing of small batches of raw material, the fundamental condition for the stability of the extremum-seeking process is breached.

$$t_D << t_{\mathrm{E}}$$

In this case, the time required for the system to move toward the extremum point (t_D) ceases to be significantly shorter than the time of its stabilization (t_{E}). As a result, the system loses its ability to effectively track the optimal operating mode. Consequently, a continuous search effect arises: the real extremum is not reached during the technological cycle, and the process proceeds within non-optimal temperature ranges, which directly leads to a reduction in the yield of the target product.

The aim of this study is to identify alternative control actions that will make it possible to eliminate or minimize the described drawbacks and to improve the efficiency of the press–extruder.

As a baseline for the present research, the model proposed in [16] is adopted, since it most fully reflects the interrelationship between temperature regimes in different zones of the apparatus and the yield of the final product, which is crucial for solving the optimization problem addressed in this work.

$$\begin{cases} \mathrm{T}_1 = \frac{qP}{MC_1} + \frac{qQl_1}{MC_1 l} \\ \mathrm{T}_2 = \mathrm{T}_1 + \frac{qP}{MC_2} + \frac{qQl_2}{MC_2 l} \\ \mathrm{T}_3 = \mathrm{T}_2 \exp\left(-\frac{\alpha q S_3}{\beta_1 M C_3}\right) + \frac{qQ_1 l_3}{MC_3 l} \\ \mathrm{T}_4 = \mathrm{T}_3 + \frac{qP}{\beta_1 MC_4} + \frac{qQl_4}{MC_4 l} \\ \mathrm{T}_5 = \mathrm{T}_4 \exp\left(-\frac{\alpha q S_5}{\beta_2 M C_5}\right) + \frac{qQ_2 l_5}{MC_5 l} \end{cases} \quad (1)$$

where T_1, T_2, T_4 are the temperatures of the raw material in the heating zones, and T_3,T_5 are the temperatures of the raw material in the sieving zones; C_1, …, C_5 are the densities of the raw material in the corresponding zones; P – the heater power; Q – the power of internal heat generation; α – the heat transfer coefficient; M – the mass of raw material passing through the extruder; q – the coupling coefficient; S_3, S_5 are the areas of the sieving zones through which vegetable oil is discharged; l_1, l_2, l_4 are the lengths of the heating zones; l_3, l_5 are the lengths of the sieving zones; β_1, β_2 are the amounts of mass transferred to the next zone.

Equation (1) can be represented in the following expanded form:

$$\begin{cases} \mathrm{T}_1 = A_1 + B_1 \\ \mathrm{T}_2 = \mathrm{T}_1 + A_2 + B_2 \\ \mathrm{T}_3 = \mathrm{T}_2 \exp\left(-\frac{A_3}{\beta_1}\right) + Q_1 B_3 \\ \mathrm{T}_4 = \mathrm{T}_3 + A_4 + B_4 \\ \mathrm{T}_5 = \mathrm{T}_4 \exp\left(-\frac{A_5}{\beta_2}\right) + Q_2 B_5 \end{cases} \quad (2)$$

The coefficients A_1, A_2, A_3, A_4, A_5 та B_1, B_2, B_3, B_4, B_5 in system (2) integrally characterize the properties of the raw material (oil content, moisture, contamination, particle size, variety, and crop type), the technological features of the equipment, and the operating conditions. Any changes in these parameters lead to corresponding adjustments of the values of Ai and Bi. For example, an increase in raw material moisture reduces the friction force, which decreases the power of internal heat generation Q and, accordingly, modifies the coefficients Bi. Thus, variation of any physical parameter affects the model coefficients.

Based on Model (2), an observer model was formed that describes the functional dependence of the yield of the target product (η) on the key parameters:

$$h = f(T_2, T_3, T_5, Q_1, Q_2, A_i, B_i) \quad (3)$$

where η denotes the amount of the useful product.

The specific analytical form of the observer model (3), obtained from Equations (2), is presented below:

$$\eta = 1 - \frac{A_5}{\ln\left(\frac{T_3 + \frac{A_4}{\beta_1} + B_4}{T_5 - Q_2 B_5}\right)}$$

where β_1 is defined as:

$$\beta_1 = \frac{A_3}{\ln\left(\frac{T_2}{T_3 - Q_1 B_3}\right)}$$

To verify the adequacy of the model, simulation modeling of the processes occurring in press–extruders was performed. The figure presents graphical dependences η = f (Q_1, Q_2) for different sets of coefficients Ai and Bi, obtained as a result of computer modeling.

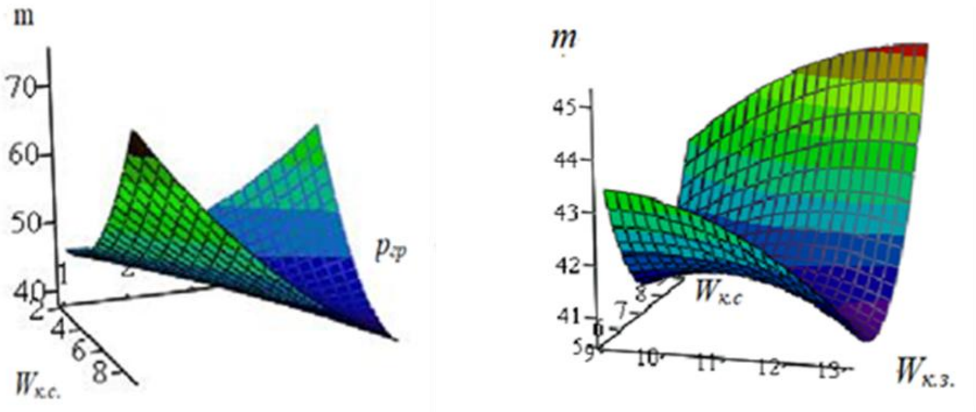

Fig. 1. Graphical dependence of the useful product yield on internal heat generation

The obtained graphical results demonstrate identity with the data published in [17]. This correspondence confirms the possibility and expediency of using a similar adaptive control framework to maximize the yield of the target product in press–extruders for oilseed crops.

2. Mathematical model of pressure

Castor seeds were investigated. Preliminary moisture–thermal treatment was carried out on a single-screw laboratory extruder of the EUM-1 type, with the possibility of regulating the screw rotational speed and changing the diameter of the die openings. Pressure in the pre-die zone, product temperature, drive power, and throughput were recorded using calibrated instruments. After extrusion, hot pressing was performed on a single-action screw press.

Regression pressure model. Based on the results of the experimental design, a regression equation for the pressure P in the pre-die zone of the extruder was obtained in the form:

$$P = 6{,}15 + 0{,}32W + 0{,}31\omega - 1120{,}31 d_M + 0{,}05\omega^2 + 684{,}77 d_{M^2} \quad (4)$$

where: W – moisture content of the extruded seeds, wt.%; ω – screw rotational speed, s^{-1}; d_M – diameter of the die forming channel, m; P – pressure in the pre-die zone of the extruder, MPa; T – product temperature in the pre-die zone, K; N – drive power consumption, kW; Q – throughput, kg/h.

The adequacy of the model was confirmed by the Fisher criterion: $F_{calc} = 0.84 < F_{tab} = 1.81$ at the adopted significance level.

The quality indicators of castor oil (peroxide value; relative tocopherol content) were evaluated for the following technological variants: without/with preliminary extrusion; unfiltered, filtered, and refined oil.

Influence of controlled parameters on pressure. Construction of the response surface based on Equation (1) demonstrates a non-monotonic effect of d_M (due to the quadratic term) and a monotonic role of ω (linear and quadratic contributions): with increasing screw rotational speed, the pressure predominantly increases; a decrease in d_M down to a certain limit raises flow resistance and pressure, whereas excessive reduction may lead to a decrease in throughput. Moisture content *W* additionally modulates *P* through its influence on friction and the rheology of the dispersed mass.

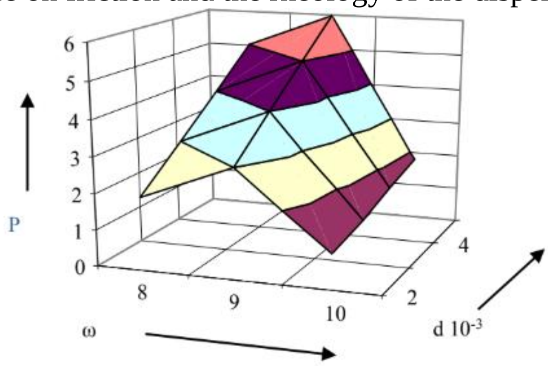

Fig. 2. Dependence of pressure in the pre-die zone P on ω and d_M (response surface according to Equation 1)

The dependences of the product temperature *T* on power *N* and throughput *Q* were experimentally established for moisture contents *W*=14, 16, 18% *W* = 14, 16, 18. At higher *N* and under conditions of increased resistance caused by a decrease in d_M, the temperature rises. An increase in *W*, all other conditions being equal, generally leads to a decrease in *T* due to heat consumption for heating and evaporation, as well as to a reduction in viscosity of the more moist mass.

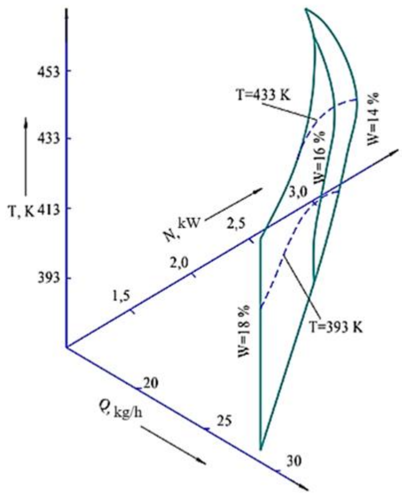

Fig. 3. Dependence T (N, Q) for W=14–18%; characteristic isotherms T≈393–433 K

Comparison of the indicators shows that preliminary extrusion contributes to a reduction in the peroxide value and an increase in the content of tocopherols relative to the baseline level (100%), which correlates with easier refining and improved thermal stability of the oil.

Equation (4) is consistent with the physics of thermoplastic extrusion of dispersed systems: the design parameters of the die and the hydrodynamics of the filled channels determine the flow resistance and shear intensity, while ω governs the shear rate, frictional heat generation, and the stress state of the product. Moisture content W affects heat transfer, phase transformations (evaporation), viscosity, and the deformation properties of the destroyed cellular structure. During subsequent pressing, this manifests itself in an increased rate of free oil release, a reduced content of phospholipids and chlorophyll in the expressed oil, and, consequently, better refinability of the product. The presence of additional tocopherols may be associated with more complete release of the microdispersed phase and a reduction in oxidative transformations under short-term thermal exposure.

5. Conclusion

Thus, the conducted study was aimed at a comprehensive solution to the problem of improving the efficiency of press–extruders for processing oilseed crops, in particular castor seeds, through the development and validation of new mathematical models.

The main scientific and practical result of the work is the development and experimental validation of a combined modeling framework that includes:

1. An improved thermophysical model (1) that describes in detail the temperature distribution across the technological zones of the extruder, taking into account key parameters: heating power, internal friction, zone geometry, and mass transfer. Transforming this model into a generalized form (2) with coefficients A_i and B_i made it possible to integrate, within a unified formalized description, a wide range of raw material properties (moisture content, oil content, particle size) and individual equipment characteristics.

2. An observer model (3) for the yield of the target product (η), analytically derived from the thermophysical model. This model provides a functional relationship between oil yield and the controllable process parameters (T_2, T_3, T_5, Q_1, Q_2), which is critically important for the future development of automatic control systems. Simulation modeling confirmed the adequacy of the model and its agreement with known literature data, substantiating the feasibility of using adaptive control algorithms.

3. A regression model of pressure (4) in the pre-die zone, which quantitatively evaluates the influence of raw material moisture (W), screw rotational speed (ω), and die diameter (d_M). The obtained model is adequate (according to the Fisher criterion) and reveals the physical nature of the process: a non-monotonic effect of die diameter (due to the quadratic dependence) and a monotonic increase in pressure with increasing screw speed. Analysis of the response surfaces clearly demonstrated the optimal operating regions for maximizing pressure.

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ДОСЛІДЖЕННЯ ЗАКОНОМІРНОСТЕЙ ПОПЕРЕДНЬОЇ ЕКСТРУЗІЙНОЇ ПІДГОТОВКИ ОЛІЙНОЇ СИРОВИНИ РИЦИНИ ТА ЇЇ ВПЛИВУ НА ПРЕСУВАННЯ

Подано результати досліджень впливу попередньої екструзійної підготовки насіння рицини на показники процесу пресування та якість одержуваної олії. На основі аналізу теплофізичних процесів запропоновано п'ятизонну модель температурних режимів екструдера з урахуванням теплообміну, масообміну та індивідуальних характеристик сировини, виведено модель спостерігача для оцінки виходу цільового продукту

На основі регресійної моделі описано зміну тиску в передматричній зоні одношнекового екструдера залежно від вологості сировини, частоти обертання шнека та діаметра формувального каналу матриці. Узагальнено експериментальні залежності температури продукту від потужності приводу та продуктивності для різної вологості, подано інтерпретацію отриманих поверхонь відгуку.

Запропонований комбінований модельный апарат дозволяє подолати обмеження існуючих систем керування, крім того модель спостерігача забезпечує можливість реалізації адаптивних алгоритмів керування, а також оптимізація параметрів екструзії дозволяє підвищити вихід олії на 12-15% та покращити її якісні характеристики.

Отримані результати формують наукове підґрунтя для створення інтелектуалізованих систем керування процесами екструзійно-пресового видобутку рицинової олії, орієнтованих на змінні властивості сировини та енергетичні обмеження обладнання. Запропонований підхід поєднує фізично обґрунтовані теплофізичні моделі з емпіричними регресійними залежностями, що дозволяє реалізувати прогнозування технологічних показників у реальному часі та формувати керуючі впливи з урахуванням критерію максимізації виходу олії за збереження її якісних характеристик. Практична цінність роботи полягає у можливості використання розробленого модельного апарату під час проєктування та модернізації прес-екструдерів для переробки олійних культур, а також у впровадженні адаптивних алгоритмів керування, що забезпечують підвищення енергоефективності процесу та стабільність параметрів готової продукції в умовах змінної вологості й фракційного складу насіння.

Ключові слова: *прес-екструдер, рицина, теплофізична модель, модель спостерігача, регресійна модель тиску, адаптивне керування, вихід олії, якість олії.*

Ф. 4. Рис. 3. Літ. 17.

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