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MODELLING OF THE PROCESS OF VYBROMECHANICAL ACTIVATION OF PLANT RAW MATERIAL HYDROLYSIS FOR PECTIN EXTRACTION

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ABSTRACT
Centrifugal and vibrational technological effects are among the main approaches to intensify the process of plant raw materials hydrolysis for pectin extraction. With the impulse intensification of such a process, it is possible not only to increase its efficiency, but also to achieve the compactness of the equipment, reduce the cost of electricity and improve the quality of the product of hydrolysis. The hypothesis is confirmed, according to which the vibro-centrifugal intensification of hydrolysis increases the driving force of the process by not only activating the material flows of raw materials and reagents, but also by reducing the resistance in the technological environment.
Graphical and analytical dependencies of the power and energy parameters of the oscillatory system were obtained, which proved the overcoming of the flow resistance of the liquid medium in the entire speed range of the drive shaft with the potential to intensify the process at a power consumption of 2.0 – 3.0 kW and or by the force of 2.3 – 2.5 kN using the Lagrange and Cauchy methods for composing and solving the equations of motion of the moving components of the tested hydrolyser with vibrating activators, and the methods of mathematical analysis and their processing in the MathCAD. The analysis of the presented parameters of the studied process of mixing the pectin-containing mass in the hydrolyser allowed us to determine the rational mode parameters of processing, which correspond to the angular velocity of the drive shaft $\omega = 150 - 150$ rad/s at the power consumption of 500 – 600 watts.

Keywords: plant raw material; hydrolysis; pectin; vibration motor; vibrator

INTRODUCTION
The process of plant raw material hydrolysis is one of the most common mass exchange processes of food technologies, in particular, the pectin extraction technologies **(Krasnikov et al., 1985)**.

There are different methods of solving the problem of removing solids outside the zone of intense mass exchange in the industry, for example, the use of ultrasound, firehoses for breaking foam, the addition of various surfactants that reduce the surface tension of the liquid. Any defoamers introduced into the solution impair the quality of the solute **(Kolyanovska et al., 2019)**. The intensification of this mass transfer process is implemented through the mixing of raw materials, which requires the study of the motion of the solid phase in the hydrolysate medium, allowing to form the necessary basis for the further theoretical study of the flow patterns and modes of hydrodynamic suspensions motion **(Bubelová et al., 2017; Zverev and Sesikashvili, 2018)**.

Mixing of raw materials in the process of hydrolysis of finely chopped fruits and vegetables for pectin extraction is implemented in the machine with mechanical or pneumatic stirring, with a fluidized bed of technological environment, with the help of the fluid or air jet, in screw and other machines with a moving and stationary solid layer. The mixing units with compressed gas and physical-mechanical volumetric activation methods based on cavitation and vibration effects are becoming widespread. The use of mechanical methods of intensifying the stirring of reagents in hydrolysers is somewhat limited due to the possibility of corrosion damage to metal surfaces and the need to use sufficiently expensive protective coatings or special methods of forming the surface layer of mixers. The erosion and corrosion products of the mixing devices further contaminate pectin, the target hydrolysis product, which is unacceptable **(Krasnikov et al., 1985; Kolyanovska et al., 2019; Czako et al., 2018)**.

Among the various forms of mechanical action on dispersion in technological processes, vibration action is one of the most effective methods for creating and correcting the required dynamic state. The adding of a vibration field on the technological environment significantly activates and intensifies the processes of heat and mass transfer, improves the quality of mixing of materials with different physical and mechanical properties, and helps to reduce the duration of technological operations and energy costs **(Palamarchuk**

et al., 2015; Sukhenko et al., 2017). The vibrating mixing effects allow for a uniform and intense mass exchange between the solid and the liquid phase and have a great potential for energy-saving technologies. Vibrating mixers, compared to conventional ones, have a higher specific performance (5-6 times higher), provide a reduction of mixing time by 2 to 3 times, metal usage by 17 %, power consumption by 30%, capital costs for manufacturing by 18 % and drive power by 30 – 35 %, which results in the decrease of the total energy consumption by 3 – 4 times **(Palamarchuk et al., 2019 a)**.

The process of hydrolysis with such stirring of a suspension of ground plant pectin-containing raw materials in hydrolysers allows increasing the propelling power of the process and energy dissipation in the technological environment. Therefore, the justification of the effective conditions of hydromechanics of the plant raw materials hydrolysis process formation based on the laws of motion of the hydrolyser working parts in the conditions of vibration centrifugal mixing of the hydrolysis suspension study, the saturation of the technological environment with energy that is necessary for the conversion of protopectin into pectin, are relevant problems that are solved in the current scientific research **(Krasnikov et al., 1985; Kolyanovska et al., 2019; Sukhenko et al., 2020)**.

Scientific hypothesis

The research is based on the scientific hypothesis, the main provisions of which are: increasing the driving force of the dissolution process, reducing the cohesive forces of the interaction of the dispersed particles with the blade and increasing the number of equilibrium conditions of the dispersed particles in a liquid dispersive medium, provided that to reduce the resistance in the liquid process mass during mixing, to increase the speed of the blade shaft and to reduce the energy consumption during the operation of the mixer; improve the quality of mixing; to improve the conditions of the bottom of the working area from sediment and to self-clean the working bodies of the sediment.

MATERIAL AND METHODOLOGY

The Lagrange equations of the second kind were used for the theoretical analysis and justification of the power and energy characteristics of the developed machine for hydrolysis of pectin-containing raw materials with vibration centrifugal excitation of the technological environment. The Cauchy method was used for solving these equations. Methods of mathematical analysis and processing in the MathCAD were also applied to obtain the necessary graphical and analytical dependencies of the basic operating parameters of the vibrating system **(MathCAD 12).**

Statistic analysis

Analysis of variance methods was used for the mathematical processing of the results of the experimental studies by means of Microsoft Excel 2013 and the statistical analysis software for crop production "AGROS".

RESULTS AND DISCUSSION

Enabling the oscillatory motion for the moving parts of the tested hydrolyser allows to reduce the resistance of the liquid technological environment during mixing, which, accordingly, reduces the energy consumption during the operation of the stirrer; increases the speed of the blade shaft; increases the degree of mixing; improves the conditions for cleaning of the bottom of the hydrolysers from the sediment; allows to carry out self-purification of the working parts from the sediment by reducing the adhesive forces of the interaction of the dispersed particles with the blade of the agitator and the cohesive forces between the particles of the raw material **(Rachmat et al., 2010; Zheplinska et al., 2019; Palamarchuk et al., 2019 b; Barbaro et al., 2009)**.

Hydrodynamic and mechanical methods for creating a non-equilibrium oscillatory system can be implemented for the equipment under study.

The hydrodynamic method involves the use of a liquid medium as an elastic component of the process, and the periodic change of pressure as a force, which greatly simplifies the regulation of the driving force, reduces the number of actuator elements and, accordingly, increases the reliability of the mechanism. At the same time, the design of the working capacity is complicated because of the need to install guides to ensure periodic braking of the flow and there is an unpredictability of its interaction with the moving fluid from the mixing of the technological environment. It is also necessary to provide an additional hydrodynamic circuit with the pump to ensure the periodic change in fluid pressure complicates the design of the hydrolysers **(Palamarchuk et al., 2013; Ha and Liu, 2009; Burger et al., 2007; Degond and Motsch, 2008.)**.

The mechanical method requires additional introduction into the system of the spring element 2 and the unbalanced unstable elements 3, the specific arrangement of which allows for linear oscillatory motion of the blade shaft 4 and, accordingly, the working blades of the machine in Figure 1.

The main disadvantages of such a model are the increase in dynamic loads on the bearing units 5 and the need to disassemble the mechanism for performing tuning operations, which are not significant enough compared with the disadvantages of the hydrodynamic system **(Nowak and Lewicki, 2004; Palamarchuk, Turcan and Palamarchuk, 2015; Palamarchuk Bandura and Palamarchuk, 2013; Ballerini et al., 2008)**.

To ensure linear oscillatory motion of the blades of the mixer, the model with a combined imbalance of the working elements under the action of circular forcing torque M_k and circular forcing force F_k was used, which causes an increase in dynamic loads on the support units and, at the same time, allows to implement more intensive oscillatory motion **(Palamarchuk Bandura and Palamarchuk, 2013)**.

The presented compelling factors of mechanical unbalance can be determined by the value of the centrifugal force *F* and the moment from the action of two forces in Figure 2:

$$F = m_d \cdot L_d \cdot \omega^2 \tag{1}$$

where: m_d – unbalanced mass; L_d – the distance from the centre of mass of unbalanced mass to the axis of rotation of the drive shaft; ω – the angular velocity of the blade shaft.

The torque is:

$$M_k = F_k \cdot a = m_1 \cdot L_d \cdot \omega^2 \cdot a = m_1 \cdot L_d \cdot \dot{\varphi}_1^2 \cdot a \qquad (2)$$

where a – the distance between the lines of action of forces F_k, φ_1 – the tilt angle of unbalanced masses m_d.

The developed system has 4 main masses and 3 degrees of freedom. The main masses of the system are the masses of unstable elements or unbalanced masses m_1, the drive shaft and bearing units on which it stands – m_2, the propeller or screw blades and the mounting unit – m_3, the scraper with the mounting unit and the brush or rubber elements for cleaning the bottom of the hydrolysers **(Bandura et al., 2015; Palamarchuk et al., 2016; Couzin et al., 2005).**

The basic degrees of freedom of the system include the angle of rotation of the unbalanced masses φ_1, the linear displacement of the drive shaft X_2, the angular displacement of the drive shaft ψ_2.

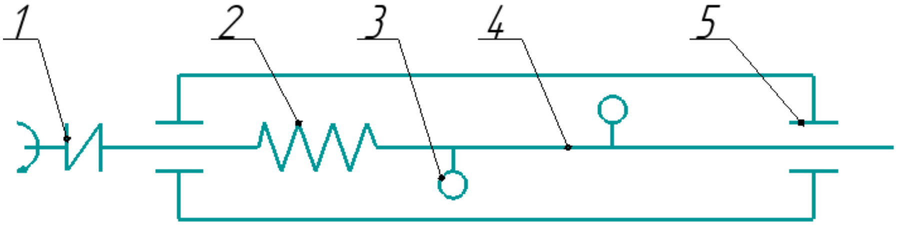

Figure 1 Model of mechanical unbalanced vibration excitation of the oscillatory motion of the blade shaft of a hydrolyser of pectin-containing raw materials: 1 – spring coupling, 2 – spring element, 3 – unstable element in the form of unbalanced masses, 4 – blade shaft, 5 – shaft bearing.

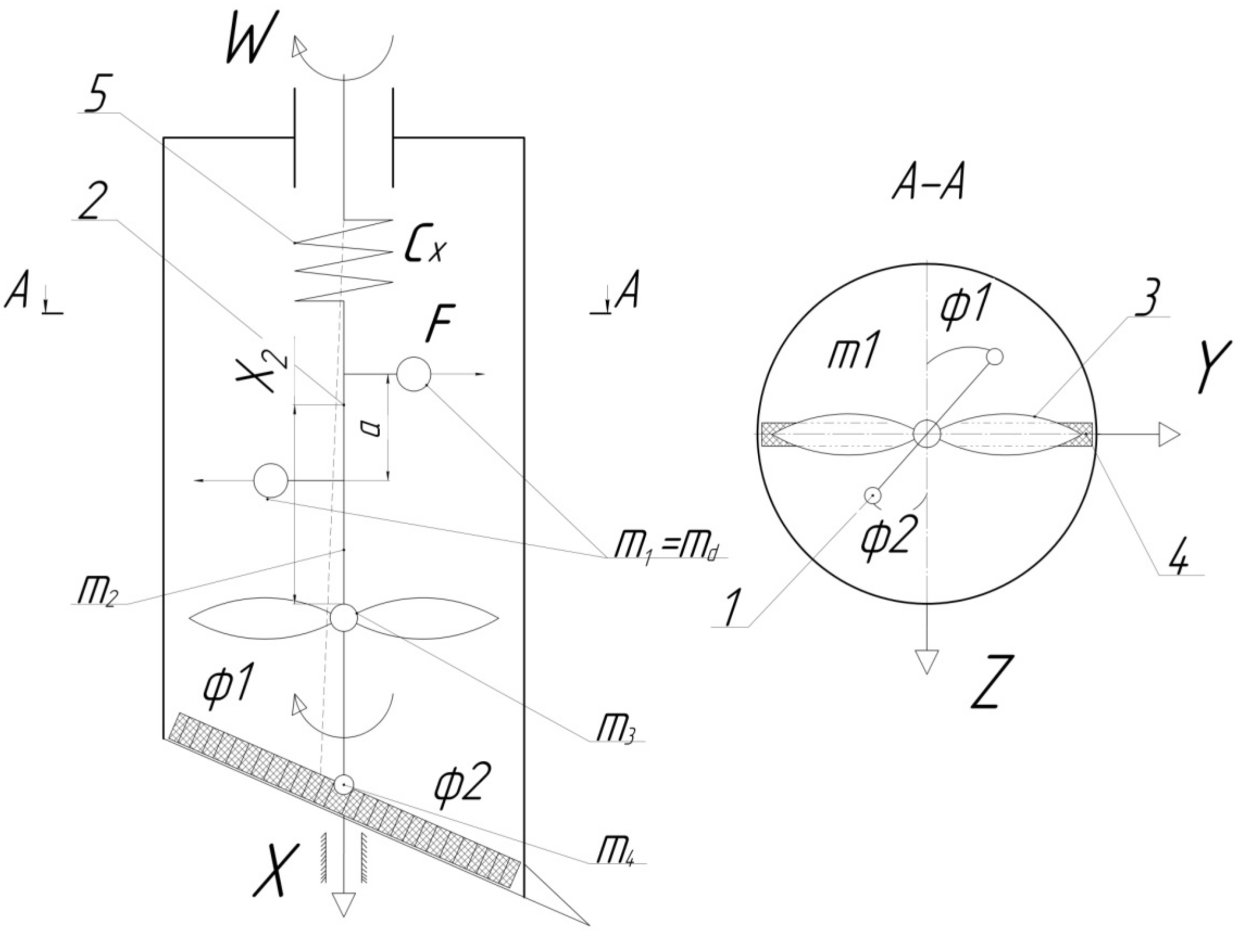

Figure 2 Calculation model of pectin-containing raw material hydrolysers with vibrating centrifugal mixer: 1 – unbalanced masses, 2 – drive blade shaft, 3 – blade, 4 – scraper, 5 - spring element with rigidity C_x.

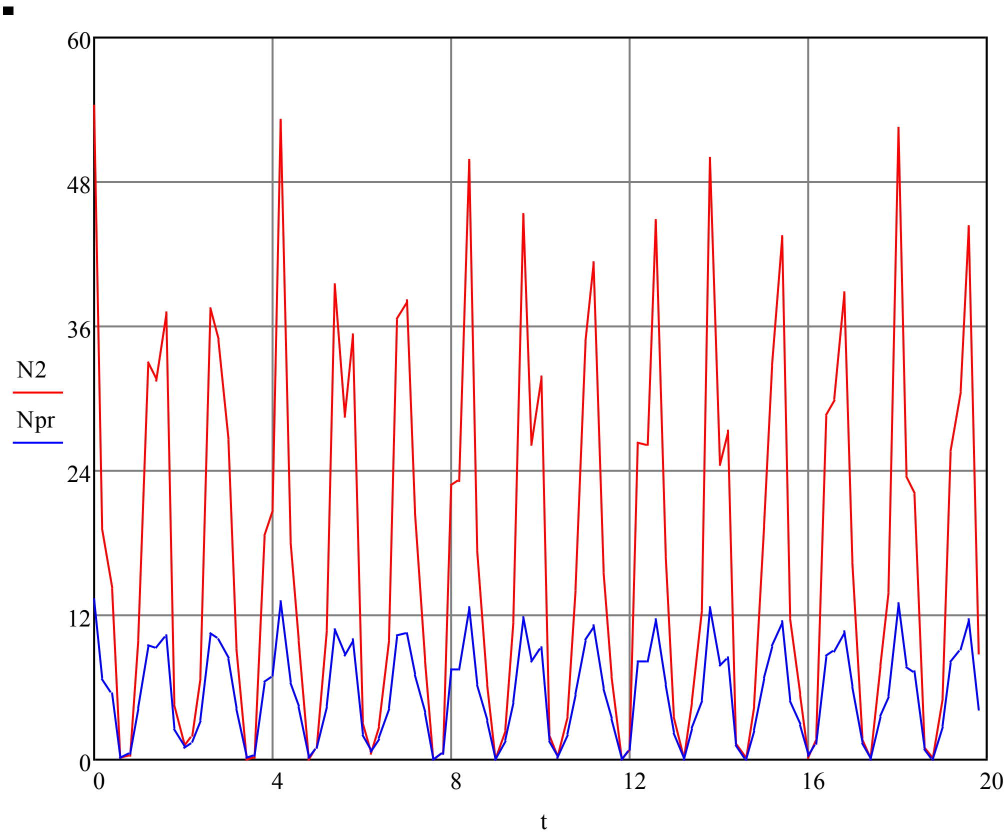

Figure 3. Energy (a) and power (b) characteristics of the system under study versus the processing time t: N_2 – power on the drive shaft of the agitator $\cdot 10^2$W; N_{pr} – the power consumption due to the resistance of the technological environment $\cdot 10^2$ W; F_2 - the driving force of the process $\cdot 10^2$ N; P_r is the resistance of the technological environment $\cdot 10^2$ N.

The Lagrange method is effective when composing the differential equations of motion of the working elements of the system, representing the desired expressions in the following system of equations:

$$\begin{cases} (\ddot{X}_2) + K_X^2 \cdot X_2 = K_m \cdot L_d \cdot (\dot{\varphi}_1)^2 \cdot (1 - f_{fr}) \\ (\ddot{\varphi}_1) + [m_1 \cdot L_d \cdot a \cdot f_{fr}] \cdot (\dot{\varphi}_1)^2 = \\ = \left[m_1 \cdot L_d \cdot \dfrac{g}{I_0}\right] \cdot \sin\varphi_1 + \dfrac{[M_{res} - P_r \cdot r_b - M_{ad}]}{I_0} \\ (\ddot{\varphi}_2) + K_\psi^2 \cdot \psi_2 = (I_2 + I_3 + I_4)^{-1} \cdot \\ \cdot \left(m_2 \cdot g \cdot r_в + m_1 \cdot L_d \cdot a \cdot (\dot{\varphi}_1)^2\right) \end{cases} \qquad (3)$$

where: k_m – mass utilization coefficient; k_x^2 , k_φ^2 , k_ψ^2 – natural oscillation frequencies; C_x ,C_φ ,C_ψ – the rigidity of the spring element relative to the free motion of the coordinate; g –the gravitational acceleration; $r_в$ – the shaft radius, P_r – the fluid resistance forces; f_{fr} – the friction coefficient; r_b – the blade radius; M_{res} – the moment of resistance; M_{ad} – the moment of resistance by adhesive forces; adhesion I_0 , I_1 , I_2 , I_3 , I_4 – the moments of inertia of the corresponding masses of the system under study.

For the composed system of equations (2), taking into account the practical aspects of the implementation of the process under study, the following assumptions can be used: given the sufficiently small angular displacement of the drive shaft, it can be neglected, i.e. $\psi = 0$; we assume that the drive shaft rotates at a constant angular velocity, i.e. ω = const; the adhesive forces of the sediment to the bottom can be neglected, i.e. $M_{зч}$=0.

The system of equations for the independent constants φ_1 and x_2 was solved using the Cauchy method, in particular, for the first two expressions were obtained:

$$X_2 = \frac{A_x}{K_X^2 \cdot (1 - \cos K_X t)} = \\ = \left[\frac{m_1 \cdot (1 - \cos K_X t) \cdot L_d \cdot \omega^2 \cdot (1 - f)}{K_X^2 \cdot (m_2 + m_3 + m_4)}\right] \qquad (4)$$

$$\varphi_1 = m_1 \cdot L_d \cdot g \cdot \frac{\left(\sin\omega t - \left(\dfrac{\omega}{K_\varphi}\right) \cdot \sin K_\varphi t\right)}{I_0 \cdot (K_\varphi^2 - \omega^2)} + \\ + \left[\frac{(M_{Kp} - P_r \cdot r_л - m_1 \cdot L_d \cdot a \cdot f_{sl} \cdot \omega) \cdot (1 - \cos K_\varphi t)}{I_0 \cdot K_\varphi^2}\right] \qquad (5)$$

where: A_x – coefficient that was introduced to simplify the expression $A_x = K_m \cdot L_d \cdot \omega^2 \cdot (1 - f)$, then $\ddot{X}_2 + K_X^2 + X^2 = A_X$, t – the operating time of the corresponding element; f_{sl} – the slipping coefficient.

Resistance, created by the fluid when the mixer's working elements rotate in it, without friction is:

$$P_r = K_0 \cdot K_{OП} \cdot S_0 \cdot (v_b \pm v_v), H \qquad (6)$$

where: K_o – the experimental coefficient; K_{op} – the optical coefficient; S_o – the area of the projection of the working element to a plane perpendicular to the velocity vector of the blade, m^2; υ_b - the blade velocity; υ_v – the velocity of the liquid.

Based on the obtained dependences (4, 5, 6) and using the MathCAD, we created the following graphs of the power and energy characteristics of the system under study, depending on the processing time t in Figure 3 and the angular velocity of the blade shaft ω in Figure 4 and Figure 5.

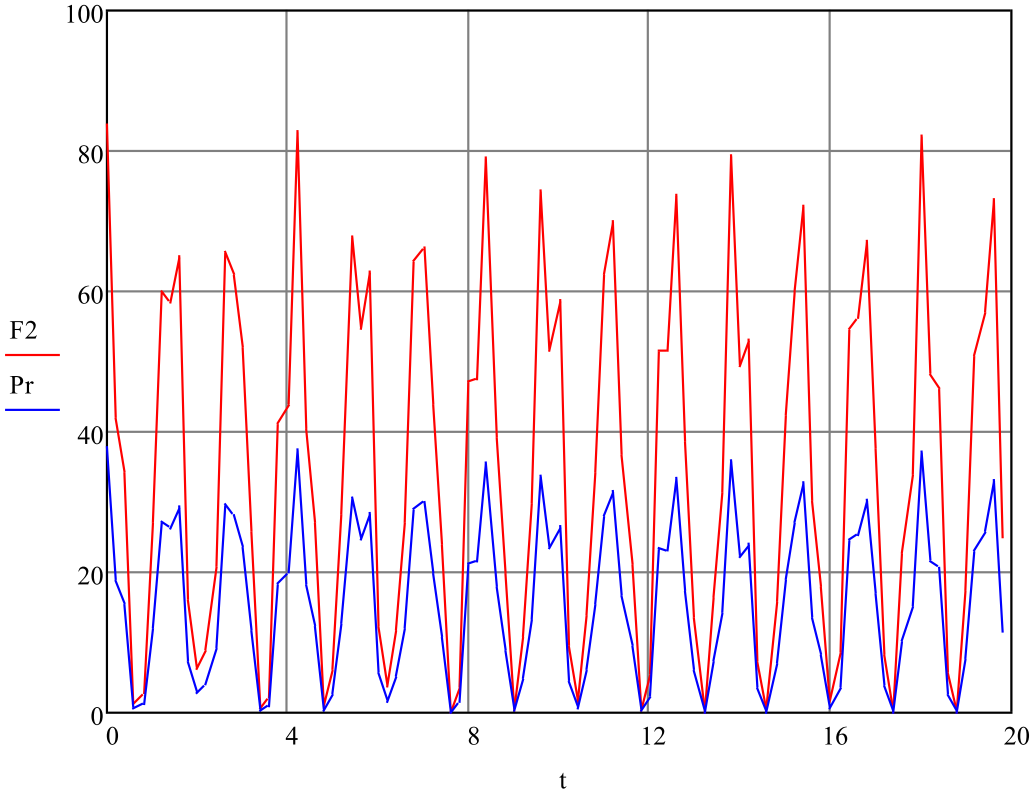

Figure 4. Energy characteristics of the system under the study N_2 and N_{pr} ($\cdot 10^2$ W) versus the angular velocity of the blade shaft ω ($\cdot 10^2$ rad/s).

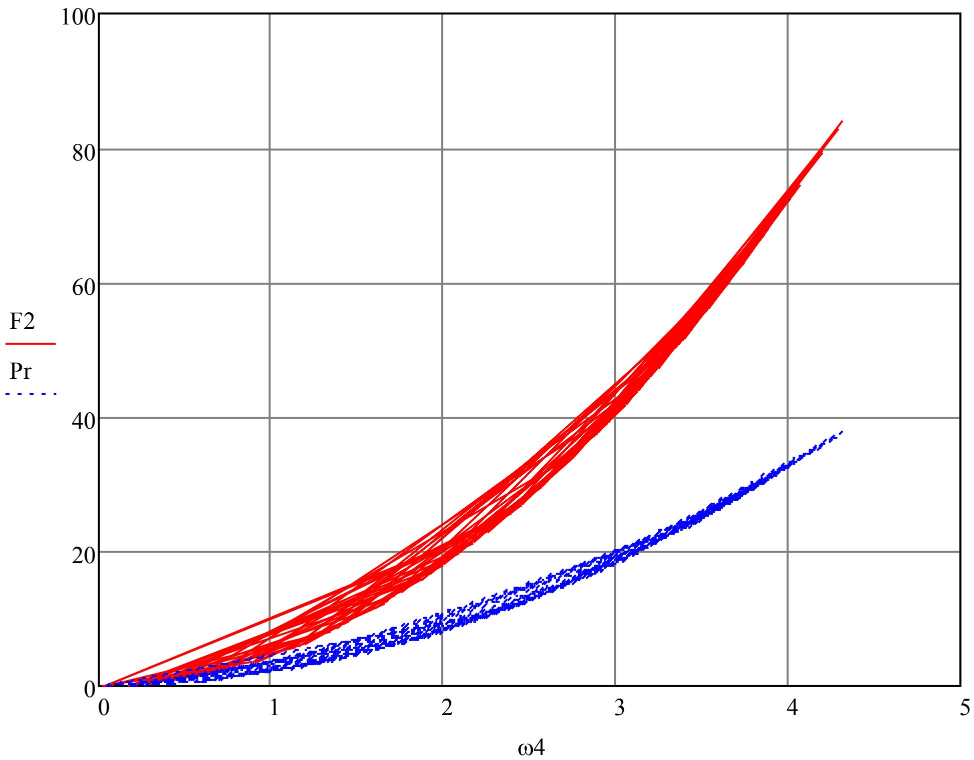

Figure 5. Force characteristics of the system under the study F_2 and P_r ($\cdot 10^2$ N) versus the angular velocity of the blade shaft ω ($\cdot 10^2$ rad/s).

Table 1 Different methods of the hydrolysis process of crushed pumpkins.

Suspension mixing conditions	Time of hydrolysis, s	Dissolved pectin content, %	Jelly-forming capacity of paste, mmHg
Without vibration, the angular speed of the stirrer shaft is ω = 150 rad/s	3600	1.5	315
With superimposing of 500 W of the vibration power using the same angular velocity	2400	2.8	378

From Figure 3 it is obvious that in the implementation of the experimental hydrolysis process with vibration centrifugal activation, the driving force is sufficient to overcome the resistance of the liquid technological environment. Also, 2.3 – 2.5 kN of driving force and 2.4 – 3.0 kW of drive motor power can be used to intensify this process **(Zavialov et al., 2015; Yanovich et al., 2015; Chuang et al., 2007; Carrillo et al., 2007)**.

For the angular velocity $\omega = 150$ rad/s of the drive shaft, the power consumption is 600W with a resistance of the fluid environment of 250W, and, if the angular velocity is doubled, the energy consumption increases by 7.2 times in Figuru 4. There is a significant increase in the technological impact of the vibration centrifugal driving force of the experimental hydrolysis process - from 1.5 kN for $\omega = 150$ rad/s to 4.6 kN for $\omega = 300$ rad/s sn Figure 5, which requires a corresponding significant energy consumption of 2.4 kW in Figure 4. Therefore, the effective angular velocity of the drive mechanism of the designed hydrolysers can be considered $\omega = 100 - 150$ rad/s, which is also recommended to provide the necessary reliability parameters of such equipment.

Pectin paste from the pumpkin "Hybrid – 75" was made on the developed hydrolysers to experimentally confirm the positive effect of hydrolysis of plant raw materials in the conditions of vibration mixing of the hydrolysis suspension.

The hydrolysis of the crushed pumpkin was performed at a temperature of 80 – 85 °C in the apparatus under a pressure of 0.05 – 0.1 MPa with 1.5 % solution of lactic acid **(UIIP, 1993)**, in the hydromodule GM 15, with the temperature of the hydrolyzed suspension during the experiment is not exceeded 65 °. After the addition of sugar syrup with sucrose content of 41% was carried out by evaporation at a temperature of heating medium 90 – 92 °C in the apparatus at a pressure of 0.1 – 0.15 MPa for 60 – 70 min. to a dry matter concentration of 68 – 70 %, with the temperature of the hydrolyzed suspension during the experiment did not exceed 70 °C. Hydrolysis was performed by mechanical stirring without the use of vibrational vibrations of the system and after vibration excitation of the shaft of the hydrolyzer.

The content of oxymethylfurfural in the finished product was determined in Ukrainian Laboratory for Quality and Safety of Agroindustrial complex according to state standard of Ukraine 7466-2001 **(DSTU 7466-2001)**. For which the permissible content did not exceed 25 mg / kg.

The standard complies with ISO 7466: 1986 Fruit and vegetable products - Determination of 5-hydroxymethylfurfural (5-HMF) content.

The results of the experiments are given in Table 1.

The Table 1 shows that the vibrational effect on the hydrolysis suspension allows to reduce the hydrolysis time by 1.5 times, increase the amount of dissolved pectin of higher quality by the jelly-forming capacity in the paste by almost 2 times.

CONCLUSION

Based on the analysis of the activation methods of technological flows during the implementation of the experimental hydrolysis process, a vibration centrifugal scheme of its intensification was selected, which potentially allows reducing the energy consumption for mixing of pectin-containing raw materials of plant suspension; increasing the driving force of the process, increasing the degree of mixing; improving the conditions of cleaning of the bottom of the hydrolysers from the sediment; and carrying out the self-cleaning of working elements.

Based on the mathematical model, analytical and graphical dependencies were obtained for the main power and energy characteristics of the process, which confirmed the overcoming of technological resistance of the liquid environment in the entire speed range of the drive shaft with the potential for process intensification at the power consumption of 2.4 – 3.0 kW, or a driving force of 2.3 – 2.5 kN.

The effective mode of operation of the drive mechanism of the designed hydrolysers is recommended: the angular speed of the shaft is $\omega = 150 - 150$ rad/s, which requires power consumption of 500 – 600 W.

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