Hydrolysis of Vegetable Raw Pectin-Containing Materials Under Vibration and Centrifugal Mixing of Liquid Environment

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Abstract. Transformation of various plant origin products with the use of heat and mass processes is one of the most common processes in the food industry. The problem of removing solid particles of inhomogeneous liquid systems outside the zone of intensive mass transfer in the industry is solved by various means, among which we can note the use of ultrasound, centrifugal forces, low-frequency oscillations. Among the multifaceted mechanical action methods on various dispersed systems in heat and mass transfer processes, vibration plays an important role. It is one of the most effective means for forming and correcting the desired state of inhomogeneous media. Creating a field with vibration action on various technological environments significantly activates and streamlines heat and mass transfer processes, improves the quality of various processes of mixing materials with properties that do not match each other, and reduces the duration of operating cycles and energy consumption. When creating a combined force and moment imbalance, both the dynamic loads on the support nodes increase, and there is a more intense oscillating movement of the blade shaft along its axis. At momentary imbalance, the loads on the support nodes are reduced while providing the desired linear oscillating motion, which is quite effective for the system under study. With the help of software and methods of mathematical and statistical analysis, graph-analytical power ratios, kinetic-energy parameters of the designed symmetry were built, which allowed substantiating energy-efficient modes of operation of the developed device.

Keywords: Unbalance elements · Oscillating system · Instantaneous imbalance · Vibrational mixing · Vibration exciter · Energy

1 Introduction

Newtonian viscous fluids' rheological properties, particularly their viscosity, are almost stable under load and do not depend on the intensity of external mechanical action,

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provided that its rate of propagation does not exceed the rate of relaxation of stresses in the medium [1]. In the conditions of rarefaction and fluidity of the dispersed mass under vibration and surfactants, unique technological conditions are achieved. They allow for compacting the highly dispersed masses as much as possible; to destroy the structure of products as much as possible to achieve maximum fluidity; control the volumetric structural and rheological properties of highly dispersed systems in the implementation of many mass transfer processes [2, 3].

The presented properties realize the possibilities of optimal use of tanks, increase transportation and storage efficiency, implement homogenization processes under optimal conditions, increase fluidity and dose of elements of the inhomogeneous system under difficult technological conditions [3, 4]. In the process of circulating motion of particles of the dispersed system in the conditions of many mutual collisions, they are breaking weak contacts and forming stronger contacts on certain parts of the surface of the material are carried out continuously. Increasing the frequency and decreasing the amplitude of oscillations while maintaining the boundary transition state accelerate this process dramatically [5].

The behavior of dispersed systems under the influence of vibration also depends on the relationship between external mechanical action and adhesion of dispersed phases in the processed products' structure [6]. Highly dispersed materials with direct point contacts and structures with coagulation contacts formed between the particles of solid phases, separated by layers of the liquid dispersion medium, are almost completely restored after destruction [7, 8]. Irreversible molding processes characterize material with condensation or crystallization structures containing contacts between phases formed after solidifying the layers between the solid phase particles (for example, as a result of heat treatment, crystallization, polymerization, plastic deformation) after loading [9, 10].

2 Literature Review

In coarsely dispersed systems, i.e., in sets of particles with sizes exceeding 1–10^3 μm, the behavior of technological loading is determined mainly by the kinematic characteristics of individual particles and the mass of the latter [11, 12]; and in microheterogeneous systems, the force factor caused by the influence of contact interactions between particles prevails. As the dispersion of technological systems increases, exceptionally when the solid phase's particle size does not exceed 10^{-5}–10^{-6} m, the properties of aggregability begin to appear in the formation of spatial structures in the technological mass [13]. This phenomenon allows us to consider highly dispersed structures as rheological objects whose behavior conditions fluidization and fluidization are similar to viscous Newtonian fluids [14]. Therefore, the level of viscosity of this system is determined by the degree of destruction of the structure, and the invariant criterion of this mass is the intensity of oscillations [15, 16].

Thus, the substantiation of effective schemes for implementing controlled imbalance of technological oscillatory systems for the formation of hydrodynamic processes is becoming more widespread to intensify mass transfer, optimizing the structural interaction of structural and technological factors, and is quite an urgent task, when converting protopectin into pectin under conditions of vibration and centrifugal mixing [17, 18].

The purpose of this research is the feasibility study of the main parameters of the oscillating system of the apparatus for the process of dissolving the hydrolysis suspension during the conversion of protopectin into pectin under vibration and centrifugal mixing due to graph analysis of changes in the driving factors of this mass transfer process. For achieving this goal, it is necessary to solve the following objectives:

- assessment of driving forces and moments and selection of the scheme of mechanical imbalance for the implementation of mechanical mixing of the liquid process mass;
- obtaining graphical dependences of power driving factors for the developed scheme of non-balancing of the studied oscillatory system;
- substantiation of regime power and kinematic parameters of executive bodies of the developed device.

3 Research Methodology

The oscillating vibrational system analysis is performed according to the kinematic, power, and energy evaluation criteria. As kinematic characteristics, we investigate the amplitude of oscillations, the angular velocity of rotation of the drive shafts of vibrators, vibration velocity, and vibration acceleration. The force analysis is performed by investigating the vibration parameters for alternative methods of unbalance of the oscillatory system by varying the inertial forces arising in the belt's support rollers during the operation of vibrators. Among the energy characteristics, we study the power consumption per drive and the specific power consumption per unit oscillating mass of the system. Synchronization of vibration exciters in the machine's support rollers is carried out to obtain such wave parameters on the working part of the belt to ensure both a stable supply of products and maximum productivity of the machine. Simultaneously, it is necessary to satisfy conditions of achievement of the necessary extraction of moisture for one pass of production on the wave conveyor.

During the empirical study in which the power, vector and energy efficiency indicators were substantiated, a laboratory installation was designed and manufactured to study the hydrolysis process with vibration and centrifugal excitation of the working medium. For this purpose, the mathematical and statistical analysis and processing of the obtained results with the help of the MathCAD application software package were used, with the help of which the basic graph-analytical dependences of the main parameters of the technological system were obtained.

4 Results

Among the main parameters characterizing the oscillatory system's imbalance, we can note the action of unbalanced forces of inertia $F_{n.zr}$ and moments of these forces $M_{n.zr}$. These factors systematize the directed forces F_n and moments M_n, which change only in magnitude. Circular forces F_k and moments M_k are changing only in the direction. Elliptic forces F_{el} and moments M_{el} can vary in magnitude and direction. The action in the oscillatory system of only the above forces causes force imbalance, only moments - momentary imbalance, and the simultaneous action of unbalanced moments and forces of inertia - combined imbalance. Variation of the above factors allows providing the executive bodies of the vibrating machine trajectories of any complexity, which can significantly increase the range of technological applications of such technical systems. However, it often leads to undesirable complications and a corresponding decrease in reliability. Therefore, we use an oscillating system with momentary imbalance for the studied process of vibration and centrifugal dissolution of pectin-containing vegetable raw materials (Fig. 1).

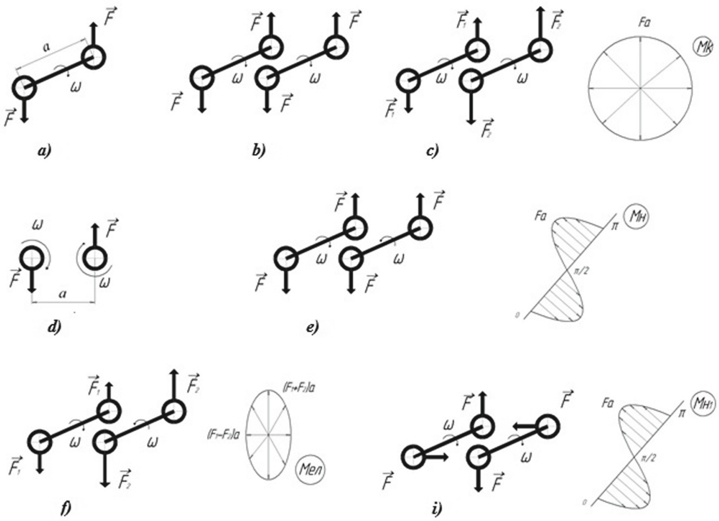


Fig. 1. Ways to create a momentary imbalance: a - under the action of a circular forcing moment M_k for a single-shaft system; b - under the influence of the circular forcing moment M_k for a two-shaft system with symmetrical load; c - under the influence of the circular forcing moment M_k for a two-shaft system with an asymmetric load; d - under the influence of the directed forcing moment M_n for uni-directional shafts with opposite loading; e - under the influence of the directed forcing moment M_n for uni-directional shafts with symmetrical loading; f - under the influence of an elliptical forcing moment M_{el}; i - under the influence of the directed moment M_n and the circular moment M_k.

The use of two-shaft circuits (Fig. 1a–f, i) to provide oscillating motion by the executive body of the studied machine complicates the design significantly. So, we preferred the scheme, which organically fits into the developed scheme of the device (Fig. 2) and presented in Fig. 1a. In the case of momentary imbalance, the support nodes' load is reduced while ensuring the desired linear oscillating motion.

The presence of inertial unbalance elements 1 (Fig. 2) leads to the emergence of centrifugal forces F, which form in the system the moment M, which brings the executive bodies out of equilibrium. Elastic elements with a stiffness C_x make restorative functions, ensuring the formation of oscillating and rotational motion of the blades 2 and cleaner 4, respectively.

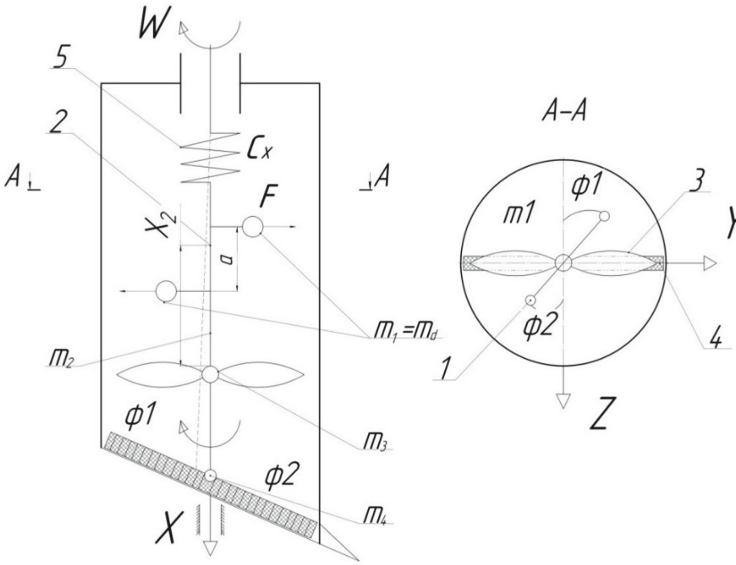


Fig. 2. Scheme of a laboratory installation for hydrolysis of vegetable raw materials with a system of imbalances: 1 – unbalanced masses, 2 – drive blade shaft, 3 – blade, 4 – scraper, 5 - spring element with rigidity C_x [19].

The following equation will calculate the size of the centrifugal force:

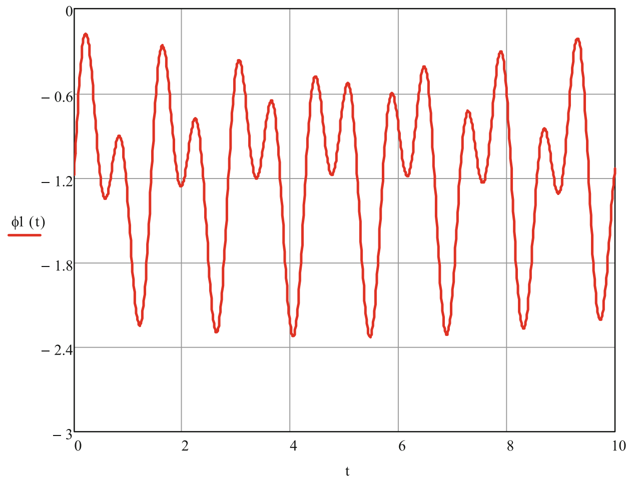
$$F = m_d \cdot L_d \cdot \omega^2 \tag{1}$$

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

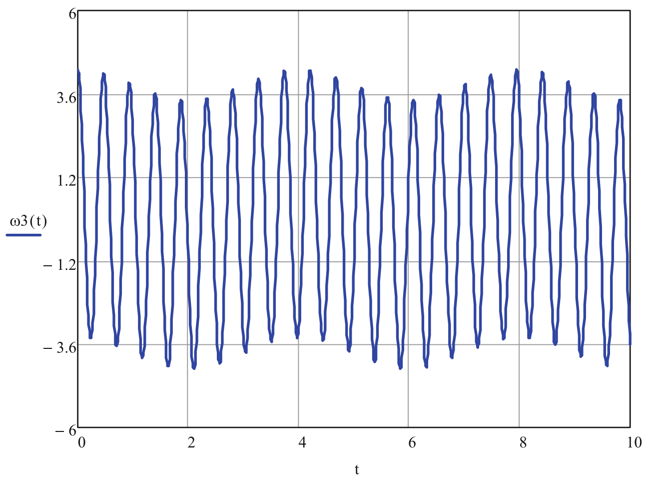
The circular mixing moment from the action of a pair of forces A is

$$M_k = F_k \cdot a = m_1 \cdot L_q \cdot \omega^2 \cdot a \tag{2}$$

The angle of twist that drives the blades of the device under study φ, as well as its angular frequency ω, have time-varying characteristics illustrated in Fig. 3.



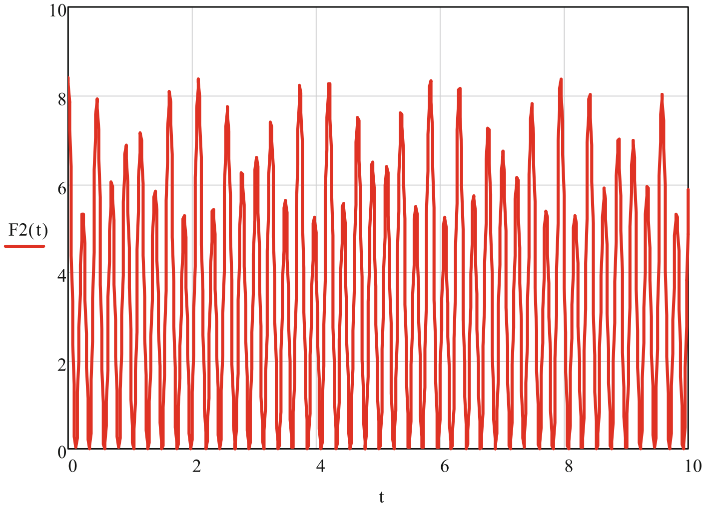
a)



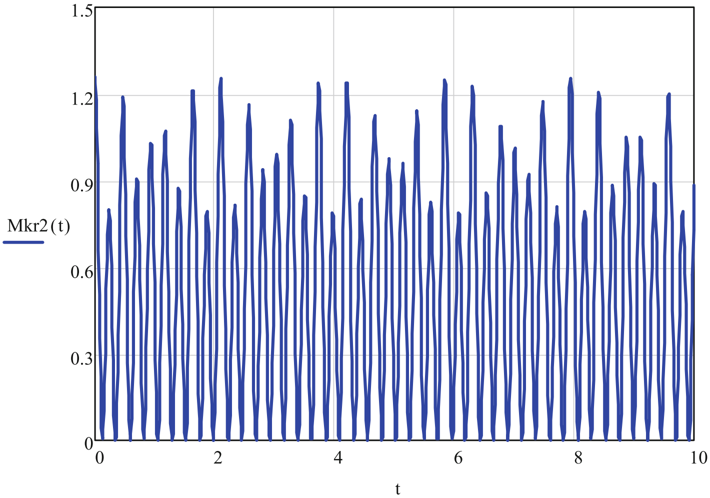
b)

Fig. 3. Changing the angle of rotation φ (a) of the blade shaft of the vibrating centrifugal apparatus for dissolution [rad] and the angular frequency ω [rad/s] depending on the processing time *t*.

The presented regularities of change of kinematic parameters of the studied oscillatory system lead to the emergence of variable unbalanced forces and moments shown in Fig. 4.



a)



b)

Fig. 4. Regularities of change of values of inertial forces (a) F [kN] and moments (b) M [kN·m] depending on processing time t.

The realization of the presented moment imbalance and the forcing circular moment M_k leads to energy consumption in the system, the change of which is shown in Fig. 6.

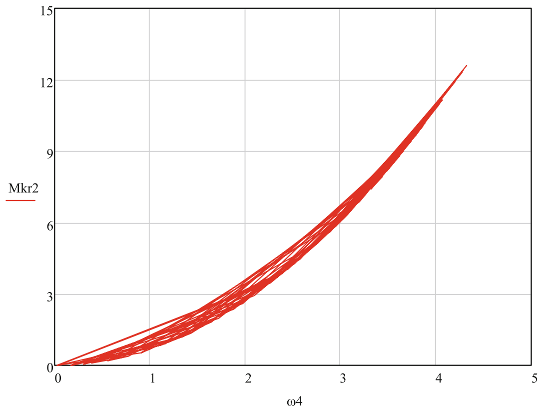


Fig. 5. Regularities of change of values of inertial circular moment *Mk* [kN·m] depending on angular frequency ω [10^2 rad/s].

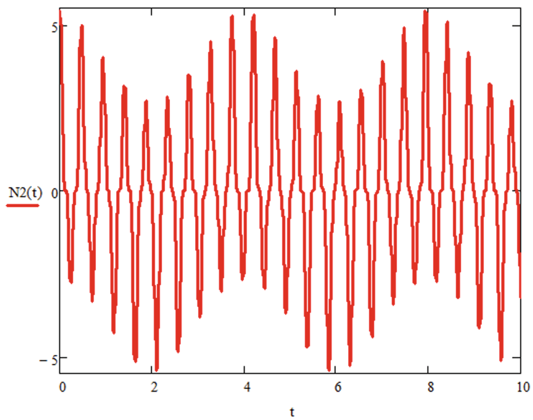


Fig. 6. Patterns of change in the amount of power consumption on the drive of the blade shaft N [kW] depending on the processing time *t* (s).

Analysis of the graphical dependencies presented in Figs. 3, 4, 5 and 6, found that at a mass of inertial unbalance elements of 1.5–2.5 kg develops a torque of 2.5–2.8 kN·m for rational modes of rotation of the drive shaft in 150–180 rad/s. The authors of scientific works [20, 21] conducted a series of similar scientific studies. They established the following rational parameters: a mass of inertial unbalance elements of 2.5–3.5 kg develops a torque of 3.5–3.8 kN·m for rational modes of rotation of the drive shaft in 200–250 rad/s, which can lead to increased energy costs. Power consumption is in the range of 600–700 W, which is quite effective in terms of technical and economic indicators of processing pectin-containing inhomogeneous liquid system, given that the provision of oscillating motion by the executive body of the studied machine will:

- reduce the resistance of the working environment when applying mixing, which will reduce energy costs during the operation of the laboratory installation;
- streamline the operating mode of the installation, which allowed to intensify mixing;
- to improve the process of sludge removal from the working area, which will reduce the cost of cleaning the working bodies of the setpoint through self-cleaning.

5 Conclusions

Based on the analysis of means of activation of liquid technological streams in the conditions of oscillatory movement of executive bodies of the mixing device, effective use of moment imbalance of system under the action of a pair of forcing forces creating a circular moment was proved; a scheme of the apparatus for dissolving pectin-containing vegetable raw materials under the action of these force factors was developed.

The mathematical analysis methods and their processing using the computer algebra system “MathCAD” have allowed obtaining graphical dependences of the oscillating system’s force and torque depending on the processing time and angular speed of the drive vane shaft. As a result, power-efficient operating modes have been justified for the developed device at 2.5–2.8 kN·m, and mass of inertial unbalance elements of 1.5–2.5 kg and an angular speed of rotation of the drive mechanism 150–180 rad/s, requiring power consumption of 600–700 W.

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