

JUSTIFICATION OF THE INFLUENCE OF LOW-FREQUENCY MECHANICAL VIBRATIONS ON THE INTENSIFICATION OF THE PROCESS OF EXTRACTION OF DESIRED COMPONENTS FROM PLANT RAW MATERIALS

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Summary: The problem to justify the influence of low-frequency mechanical vibrations on external mass transfer under the conditions of vibroextraction from plant raw materials and establish the regularities of its change depending of the mode parameters of the process was stated. The intensive renewal of the contact surface of phases in vibroextractors was achieved due to the mode parameters of the process (frequency and amplitude of vibrations of the vibrotransporting system). The established functional dependence of saturation of the extract by extractive substances with time on the volume mass-transfer coefficient will enable us to determine the minimum time for which the system achieves the equilibrium state of not only extraction processes, but also of the processes that are accompanied by mass exchange in apparatuses with mixing devices. The conclusions and results of the mathematical modeling under the conditions of vibroextraction agree with the results of the experiments.

Keywords: vibroextraction, mathematical model, scaling, hydrodynamics, structure of flows, mass transfer, convective diffusion.

Introduction

The development and improvement of extraction equipment or the investigation of its operation are connected with the calculation of its mass-exchange characteristics. Both the exactness of other calculations and the possibility of their performance on the whole depend on its completeness and perfection. For the development of an extractor, in accordance with its capacity in terms of the solid phase or extract, it is necessary to know the kinetic coefficients, namely, the diffusion coefficient of the soluble substance inside the plant raw material and coefficient of mass-transfer from the surface of the solid body to the extractant. After calculating the kinetic coefficients, establishing their change with time in the process and their dependence on the hydrodynamic conditions and technological parameters of the process, it becomes possible to determine the optimal time of the process, final concentrations of the soluble substance in the solvent cake and extractant, and design parameters of the apparatus. At the same time, it should be noted that a desired component may be located in pores of a raw material in the soluble state, which is characteristic for an unfractured fresh plant cell, or in the form of a solid soluble substance in a dried raw material treated chemically, by electric current, baric effects, or squeezed out mechanically. The indicated influential effects cause the accompanying initial stage of another process, namely, the dissolution of desired components in capillaries, pores, and destroyed cells. These complex circumstances lead to certain difficulties and errors in calculations of the indices of convective mass transfer because materials subjected to extraction differ in their physicochemical properties, particle size,

etc., which, in turn, requires an individual technological mode and, therefore, implementation of the process. Thus, the extensive introduction of new advanced vibroextraction equipment requires the theoretical justification of the features of the mass-transfer mechanism during vibroextraction on all its scale levels.

In view of the aforesaid, we stated the problem to justify the influence of low-frequency mechanical vibrations on external mass transfer under the conditions of vibroextraction from plant raw materials and establish the regularities of its change depending of the mode parameters of the process.

Materials and Methods of Investigations

The process of continuous vibroextraction from plant raw materials (hop, sugar beet, and loose-leaf black tea) was investigated on a physical model of a continuous vibroextractor [1], whose body consists of side-bars with an internal diameter of 0.3 m and a height of 0.4 m. To feed ground plant raw materials to the apparatus, the lower side-bars at a level of 0.2 m from the bottom is connected to a charging device made in the form of a U-shaped glass tube 0.15 m in diameter with a watering pot through a screw. To feed the extractant, a shower spreader of the extractant and a discharge tray for the solvent cake are fixed on the last upper side-bar. Inside the body, a balanced vibrotransporting device, which consists of a system of vertical rods with transporting plates of special design, fixed horizontally on them, is located [1]. In operation of the apparatus, low-frequency mechanical vibrations are transferred to the vibrotransporting system through the rods of vibrodrive. The frequency of rotation of the shaft of the electric motor and simultaneously the frequency of vibrations of the vibrotransporting system of at most 10 Hz was provided by an autotransformer, and fixed amplitudes of $5 \cdot 10^{-3}$, $10 \cdot 10^{-3}$, and $15 \cdot 10^{-3}$ m were set.

The ground plant raw material prepared for vibroextraction was fed by the screw through the feeding device to the lower plate, moved continuously along the height of the apparatus with the help of vibrotransporting plates as a counterflow relative to flow of the extractant with the gradual extraction of the desired components and was unloaded from the apparatus in the form of solvent cake (pulp) through the tray, and the extract was removed through a filtration partition in the lower part of the apparatus.

To provide the thermostatic effect, the vibroextractor is equipped by an internal and an external electric radiator. For the sampling of the extractant from each cell, a sampling device was mounted in the zone of the vibromixing device.

To grind the root of sugar beet, we used a meat comminutor with a diameter of holes of the outlet grate of $12 \cdot 10^{-3}$ m. The dried hop raw material was used in the natural state.

After filling of the working volume of the apparatus by the extractant and reaching the steady-state temperature at a level of 346–351 K, the vibrotransporting device was turned on. The predetermined mass ratio of the solid phase and liquid phase was provided by regulating the rotational frequency of the screw of the feeding device.

The contents of dry water-soluble substances in extractant samples and in the tissue of the raw materials were determined by the refractometric method (RPL-4 refractometer).

Results and Discussion

Determination of the Regular Mode of Extraction of Soluble Dry Substances

In processing of experimental data, the calculation of the kinetic coefficients was performed by the Akselrud method for a counterflow process with isolation of a regular mode [2, 3]. For instance, for the i th moment of time of the process, we determined the parameter $\beta = (C_i - C_n)/(C_0 - \bar{C})$, where C_0 and \bar{C} are, respectively, the initial and the volume-mean concentration of the substance in the solid phase, C_n and C_i are, respectively, the initial and the current concentration of the substance in the extractant. For each projected experimental mode, we determined the dependence $\lg\left(\frac{1}{1+\beta} - \frac{1}{\beta} \frac{C_i}{C_0}\right) = f(\tau)$ with isolation of the regular mode of the process (linear segment), for which the kinetic equation is an exponent

$$\frac{C_0 - \bar{C}}{C_0 - C_n} = \frac{1}{1+\beta} - \sum_{n=1}^{\infty} A_n n e^{-\mu_n^2 \tau} \quad (1)$$

where $\lg(A_1)$ is a segment on the ordinate axis cut by the line of the regular mode and μ_1 is the root of the characteristic equation.

According to the adopted method, for particles the shape of which is close to a spherical one, in calculations of μ_1 , the Biot criterion, and molecular diffusion coefficient D , we used the following system of equations:

$$\begin{cases} A_1 = \frac{6}{(3\beta - \mu_1^2/\text{Bi})^2 + \mu_1^2(1 - 1/\text{Bi}) + 9\beta}; \\ 0,434\mu_1^2 D/R^2 = \text{tg}(\alpha); \\ \text{ctg}(\mu_1) = \frac{1}{\mu_1} + \frac{1}{3\beta/\mu_1 - \mu_1/\text{Bi}}, \end{cases} \quad (2)$$

where the parameter is
$$\delta = \frac{1}{6} \left[\left(\frac{\mu_1^2}{1 - \mu_1 \text{ctg}(\mu_1)} - 0,5 \right)^2 + \mu_1^2 - \frac{1}{4} \right], \quad (3)$$

or, with regard for the graphical interpretation,
$$\delta = \left(\frac{1}{A_1} - 1 \right). \quad (4)$$

By analogy, for particles the shape of which is taken to be close to a platelet shape, the system of equations for the calculation of the corresponding parameters has the form

$$\begin{cases} A_1 = (\mu_1^2 / \text{Bi} - \beta)^2 + \mu_1^2 (1 / \text{Bi} + 1) + \beta; \\ 0,434\mu_1^2 D / R^2 = \text{tg}(\alpha); \\ \text{ctg}(\mu_1) = \mu_1 / \beta - \text{Bi} / \mu_1, \end{cases} \quad (5)$$

where R is the radius of a spherical particle or the half-thickness of a particle the shape of which is close to a platelet shape, and α is the slope of the kinetic curve.

Taking into account the positive experience in the study of regularities of mass transfer of desired components from plant raw materials and methods for the quantitative evaluation of mass exchange in the field of low-frequency mechanical vibrations, by the Akselrud method, which assumes the isolation of the stage of the regular mode of the process, we performed a series of the corresponding experiments with their graphical interpretation, which is presented in Figs. 1–3. For this purpose, experimental curves of the kinetics of extraction of desired components from the investigated raw materials were constructed on the semilogarithmic coordinates $\xi=f(\tau)$, where $\xi = \lg(1/(1+\beta) - C_i/(\beta C_0))$.

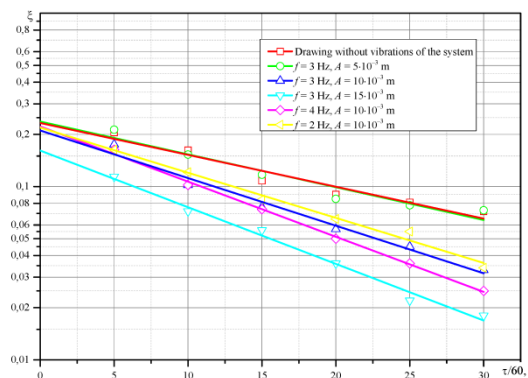


Fig. 1. Experimental curves of the kinetics of extraction of dry substances from beet raw material with separation of the regular process mode.

It is clear that the graphs presented in Figs.1–3 are auxiliary for the calculation of the kinetic coefficients of the process. At the same time, attention should be paid to the fact that they differ in slope of the lines depending on the quality of external mass exchange. In other words, the increase in the interface turbulence leads to an increase in the slope of the segments of the graph with the isolated regular mode.

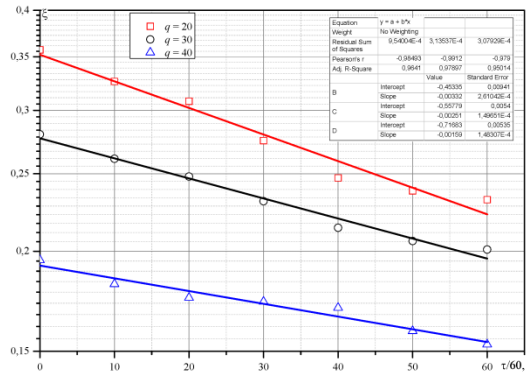


Fig. 2. Experimental curves of the kinetics of extraction of dry substances from the hop raw material with isolation of the regular process mode.

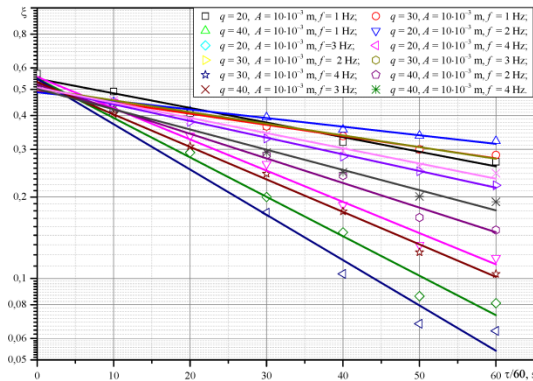


Fig. 3. Experimental curves of the kinetics of extraction of dry substances from the hop raw material with separation of the regular process mode.

During determination of the design and technological parameters of the process (hydromodulus, temperature, and loading of the apparatus with respect to the solid phase), the intensification of the process can be achieved due to the mode parameters of the process (frequency and amplitude of vibrations of the vibrotransporting system). The joint action of these parameters is represented by the so-called intensity of vibrations, which is equal to the product of the amplitude by the frequency.

Generalization of the Results of Investigations

The results of the investigations on the influence of the intensity of vibrations of the vibrotransporting system on external mass exchange for the beet raw material are shown in Fig. 4.

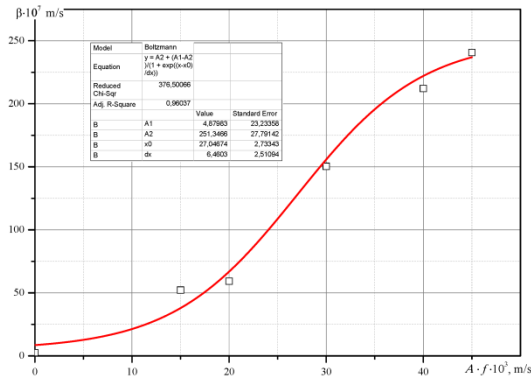


Fig. 4. Influence of the intensity of vibrations of the vibrotransporting system on external mass exchange during extraction of sugar beet (specific load is $B = 300 \text{ kg/m}^3$).

It is clear that, with increase in the intensity of vibrations, the activation of the interface surface increases as a result of the decrease in the condition of shielding of raw material particles by one another.

The obtained analogous generalizing results for the hop raw material shown in Figs. 5 and 6 agree with the previous results obtained for the beet raw material shown in Figs. 3 and 4. In other word, the intensity of vibrations of the vibrotransporting system, beginning from $30 \cdot 10^3 \text{ m/s}$, intensifies substantially external mass transfer and facilitates the transition of the hop raw material into the pseudo-liquefied state, and the graphical reduction in mass transfer during the increase in the hydromodulus of the process is explained by the limitation of its internal mass transfer. This is why, on the last two graphs (Figs. 4 and 5), a certain “foliation” of curves with respect to the factor q , which denotes the mass ratio of the liquid phase to the solid phase, is observed.

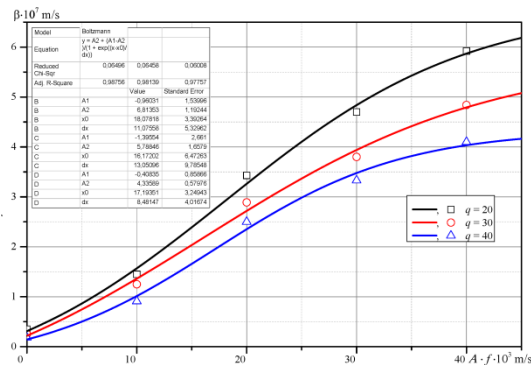


Fig. 5. Influence of the intensity of vibrations of the vibrotransporting system on the external mass exchange during extraction of the hop raw material.

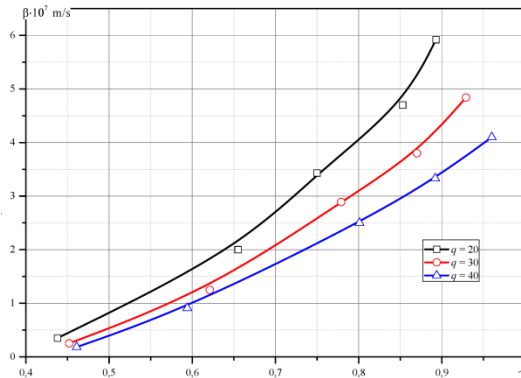


Fig.6. Dependence of the mass–transfer coefficient on the degree of activity of the surface of the hop raw material.

Mathematical Description of the Process

Along with general regularities that characterize the intensity of mass exchange in the extraction apparatus, the implementation of the process, which forms the features of the hydrodynamic conditions of its realization, plays a significant role. For this reason, for the determination of the relationship between the design and technological parameters of the process justified in the given technological limits, the use of the analytical theory is an efficient method.

At the same time, the extensive introduction of the new vibroextraction apparatuses requires the theoretical justification of the features of the mass transfer mechanism under vibroextraction at all its scale levels.

To intensify the process and choose the method and implementation of the process, it is necessary to know the mechanism of intensification, the diffusion properties of plant raw materials, the statics and kinetics of the process in each stage.

To establish the functional dependence of saturation by extractive substances of extract with time on the volume mass–transfer coefficient, we represent the motive force of the process in terms of the difference between the concentration of the extractive substances on the interface and its concentration in the volume of the extractant provided that, on the interface, the resistance of mass exchange is absent as a consequence of the activation of the interface by turbulent pulsing flows, which is realized by vibromixing devices:

$$\begin{cases} dC/d\tau = K_v (C_p - C) \\ C(\tau_0) = C_0 \end{cases}, \quad (6)$$

where $dC/d\tau$ is the change in the current concentration of the substance in the extractant, K_v is the volume mass–transfer coefficient, C_p is the equilibrium concentration of the substance in the extractant, and τ is the current time.

To solve this equation, we use the method of separation of variables, according to which, we rewrite Eq. (6) in the form

$$\frac{dC(\tau)}{C_p - C(\tau)} = K_v d\tau \quad (7)$$

Further, we take indefinite integral of the left-hand and the right-hand-side of the equation

$$\int \frac{dC(\tau)}{C(\tau) - C_p} = -\int K_v d\tau, \quad (8)$$

whence we get

$$\ln(C(\tau) - C_p) = -K_v \tau + \alpha \quad (9)$$

where α is the constant of integration ($\alpha = \text{const}$).

From the last relation, we determine $C(\tau)$

$$C(\tau) = C_p + e^{-K_v \tau} e^\alpha \quad (10)$$

To find the unknown constant α (or e^α), we substitute $\tau = \tau_0$ into this expression. Then, in view of the condition $C(\tau_0) = C_0$, we have

$$C(\tau_0) = C_p + e^{-K_v \tau_0} e^\alpha = C_0 \quad (11)$$

whence we obtain

$$e^\alpha = e^{K_v \tau_0} (C_0 - C_p) \quad (12)$$

Substituting e^α into Eq. (10), we finally have

$$C(\tau) = C_p + e^{-K_v \tau} e^{K_v \tau_0} (C_0 - C_p) = C_p + e^{-K_v (\tau - \tau_0)} (C_0 - C_p) \quad (13)$$

If the initial conditions of functioning of the process are such that, for $\tau_0 = 0$, the initial concentration of the substance is zero, i.e., $C_0 = 0$, then from the last equation we obtain

$$C(\tau) = (1 - e^{-K_v \tau}) C_p \quad (14)$$

Thus, the obtained mathematical model can be used for the evaluation, prediction, and optimization of extraction processes because it establishes the relationship of the change in the current concentration of the extraction system with the time of the process and the volume mass-transfer coefficient, which determine the structural, mode, and technological parameters of the process.

Conclusions

The intensive renewal of the contact surface of phases in vibroextractors is achieved due to the mode parameters of the process (frequency and amplitude of vibrations of the vibrotransporting system). This gradual increase in the intensity of vibrations, beginning from about 15–20 m/s, leads to an abrupt increase in the mass-transfer coefficient, stabilizing at a certain level as a result of a decrease in the conditions of shielding of particles of the raw materials between one another, which, in turn, means the transition of the raw material into the pseudo-liquefied state. This is why, from this moment only internal molecular diffusion remains a limiting stage of the process of extraction of the substances.

The established functional dependence of saturation of the extract by extractive substances with time on the volume mass-transfer coefficient will enable us to determine the minimum time for which the system achieves the equilibrium state of not only extraction processes, but also of the processes that are accompanied by mass exchange in apparatuses with mixing devices. The conclusions and results of the mathematical modeling under the conditions of vibroextraction agree with the results of the experiments.

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