Regularities of Solid-Phase Continuous Vibration Extraction and Prospects for Its Industrial Use

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Abstract. The results of the substantiation and hardware design of continuous vibroextraction for solid-liquid systems with a small difference in the density of phases are presented, which provide the possibility of determining the rational constructive and technological parameters of vibroextractors and modes of their industrial exploitation. Mathematical modeling and methods of experimental evaluation of the mass transfer efficiency are based on the phenomena of non-stationary mass transfer and hydrodynamics. The mechanism of counter-phase separation of phases during the continuous process and features of mass transfer at all scale levels are described. Theoretical substantiation is given to convective mass transfer taking into account the accumulation component of the substance, which, taking into account the mass return in the zone of mixing, is what discloses the content of this component. The realization of the obtained results allowed to develop the engineering calculation method of vibroextraction in the food industry, high-efficiency energy-saving vibroextractors of continuous action and, based on them, apparatus-technological schemes of rational deep processing of plant raw material for a number of industries.

Keywords: Vibroextraction · Mathematical model · Hydrodynamics ·
Mass transfer · Diffusion · Pulsating flow

1 Introduction

In spite of all the diversity of modern extraction technologies for solid body-liquid systems with a small difference in the density of the phases, both in the chemical and food industries, there exists a number of common disadvantages due to the lack of porosity of fine fractional raw materials for countercurrent continuous extraction. These problems are especially relevant for the most energy- and material-intensive branches of the food industry, such as sugar, fat, canning, wine-making, brewing, alcoholic, starch-maltodextrin and pharmaceutical, where millions of tons of plant raw materials and their waste are processed annually [1]. Therefore, for these purposes, vibration extractors are the most promising ones as they provide intense inter-phase mass transfer regardless of the degree of raw material shredding [2, 3].

The article solves the scientific and technical problem of improving vibroextraction processes in the food industry, which will provide the opportunity to determine the rational structures and parameters of vibroextractors and their modes of operation.

2   Literature Review

This process implements a new principle of reverse flow phase separation with the help of vibrotransport devices of a special design, which do not cause the pressing of the layer of raw materials and ensure its porosity, regardless of particle size [4]. Turbulent pulsating jets generated by the transport elements of the vibration nozzles form optimal hydrodynamic conditions for intensive micro-mixing and, as a consequence, conditions for the creation and renewal of a large interphase surface in cross-sections of the two-phase flow in the entire working volume of the apparatus. In this case, the duration of all particles in the working volume of the apparatus is almost the same [5, 6]. However, vibration extraction is a relatively new technological process. Its general theory is complex and is at the very beginning of its development. Until now, a number of important issues related to the theory and practice of the process have remained unexplained. It is required to establish the features of phase separation mechanisms in the working volume of the apparatus, mass transfer at all scale levels, and others.

3   Research Methodology

Research methods include experimental and analytical methods of modeling. The mass exchange characteristics of vibroextraction were obtained by methods based on the classical regulations and laws proposed by prof. Lysianskyi, Axelrod, using standard methods of determining qualitative indices of extracts and methods of control for sugar and brewing industries. The establishment of the diffusion characteristics of raw material tissue was carried out by water-soluble dry substances. During research, hops, sugar beet and black tea were used. As an example, the results for the extraction of dry water-soluble substances from sugar beet are presented [1].

4   Research Methodology

4.1   Design Features of a Continuous Vibroextractor

The process of continuous vibration extraction was investigated based on the developed model of a continuous action vibroexctractor according to the scheme in Fig. 1 [1]. The apparatus is filled with an extractant through distributor 3. At the same time a given amplitude-frequency mode of oscillation of the vibration transport system is set. Prepared for extraction, the shredded vegetable raw material is fed through feed device 2, goes under the bottom plate while being continuously concurrently propagated along the apparatus using vibration transport plates with the gradual removal of the target components, and is then unloaded from the apparatus in the form of meal
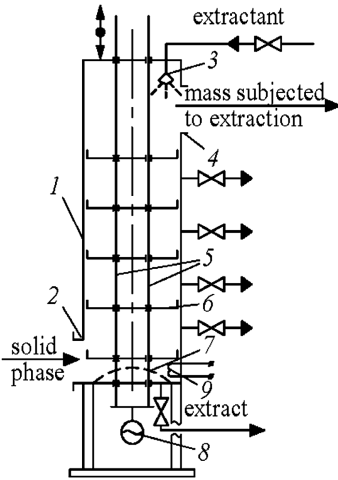
Fig. 1. Scheme of vibroextractor of continuous action: (1) body; (2) feeding device; (3) shower distributor; (4) tray; (5) stock; (6) plate; (7) filter; (8) engine; (9) heating element.

through tray 4. The finished extract is removed from the device through filter 7. To provide the temperature regime the apparatus is equipped with electric heating 9. Samplers are mounted in the installation zone of the vibration mixing device for the sampling of an extractant from each cell. A meat-cutting machine with a grating hole diameter of 12×10^{-3} m was used to shred the sugar beet root. The temperature regime was maintained at the level of 346–351 K; amplitude of oscillations 5, 10, 15 mm; frequency: 2–4 Hz. The ratio of solid and liquid phases was achieved by adjusting the rotation frequency of feeder screw 2.

Countercurrent phase separation (Fig. 2) is carried out using the difference in the hydraulic resistance of the working fluid flow through the transport open elements with flexible pipe 2 installed on them, as well as using the filtering effect through the filter elements 3 and the sedimentation of the solid phase particles on the surface of the plates with board 4. When the plates move down (Fig. 3a), the suspension is pushed through the transport element with a flexible pipe 2. The formed jet of the suspension moves outside the pipe.
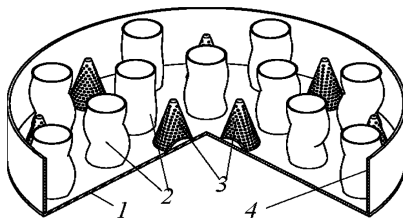

Fig. 2. Plate with flexible transport elements: (1) plate; (2) transport flexible elements-pipes; (3) filter element; (4) board.
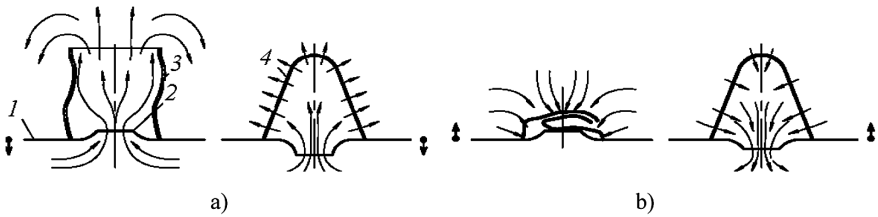
Fig. 3. Schemes of the movement of working flows in the transport and filter elements of the plate with a flexible pipe: (a) downward movement of the plate; (b) upward movement of the plate.

When the plates move up (Fig. 3b), the flexible pipe loses its shape, formed by a flow, and holds the solid phase on the surface of the plate.

In this case, the extractant is filtered through the holes of the filter elements and passes on other side of the plate. After some time, a growing layer of the solid phase gets into the zone of turbulent jets generated by the filter elements of the upper plate, activated by the intensive relative phase movement, then gets under the transporting elements of the upper plate, and the process of transportation is repeated until the moment of unloading the solid phase from the apparatus.

Standing on the periphery of the side plates is intended to hold solids on the surface, increasing the separation effect of phases and preventing the flushing of small fractions of solid phase outside the plate [7].

4.2   Investigation of Mass Transfer

The results of studies on the effect of low-frequency mechanical vibrations, as sources of pulsating vibration turbulent variable jets in a liquid-solid system, on the intensity of mass exchange during extraction from plant raw materials, are presented, for example, for sugar beet. It should be noted that the target component in the raw material may be located in pores in the soluble state, which is characteristic of an undestroyed fresh plant cell, or as a solid soluble substance in dried raw material which is chemically treated by an electric current or baroeffects, or is mechanically depressed. The last influential effects cause the presence of the initial stage of another process - the dissolution of target components in capillaries, pores or destroyed cells. Such difficult circumstances give rise to some difficulties in calculations, since the extracted materials differ in their physical and chemical properties, particle sizes, etc., which in turn requires an individual technological regimen and, accordingly, hardware design of the process [8, 9].

In view of the above, the task was not only to calculate the coefficients of molecular diffusion for typical investigated types of plant material (hops, tea, grain), but also to establish the regularities of their change from regime parameters of the process.

The calculation of kinetic coefficients was carried out using the Axelrod method for the straightforward process, with the allocation of the regular regime of the process [9, 10]. Thus, for each time point the parameter was determined $\beta = (C_1 - C_i)/(C_0 - \overline{C})$, where C_0 and $\overline{C}$ are, respectively, initial and average solids volume concentrations of

the substance; C_i and C_1 are, respectively, initial and present concentrations of the substance in the extractant. For each experimental regime the dependence was established $\lg(1/(1+\beta) - C_1/(\beta C_0)) = f(\tau)$ with the allocation of a linear section for which the kinetic equation is an exponent: $(C_0 - \overline{C})/(C_0 - C_i) = 1/(1+\beta)$ $- \sum_{n=1}^{\infty} A_1 n e^{-\mu_1^2 n \tau}$, where $\lg(A_1)$—segment on the ordinate, which cuts by line; μ_1— root of characteristic equation.

According to the accepted method for particles whose shape approaches that of a sphere, the μ_1 calculation, the Bio criterion, and the molecular diffusion coefficient D used a system of equations:

$$\begin{cases} A_1 = 6/\left[(3\beta - \mu_1^2/\mathrm{Bi})^2 + \mu_1^2(1 - 1/\mathrm{Bi}) + 9\beta\right]; \\ 0.434\,\mu_1^2 D/R^2 = \mathrm{tg}(\alpha); \\ \mathrm{ctg}(\mu_1) = 1/\mu_1 + 1/(3\beta/\mu_1 - \mu_1/\mathrm{Bi}), \end{cases}$$

where the parameter $\delta = \left[(\mu_1^2/(1 - \mu_1 \mathrm{ctg}(\mu_1)) - 0.5)^2 + \mu_1^2 - 1/4\right]/6$, or, taking into account the graphic interpretation, $\delta = 1/A_1 - 1$.

Thus, a series of relevant experiments from their graphic interpretation are shown in Fig. 4. For this purpose, experimental curves of the kinetics of extracting the target components from the experimental raw material under the given regime and technological parameters, where $\xi = \lg(1/(1+\beta) - C_1/(\beta C_0))$, were constructed in half-logarithmic coordinates $\xi = f(\tau)$. As it can be seen, the shown graphs are auxiliary for calculating the kinetic coefficients of the process. The increase in interphase turbulence leads to an increase in an inclination angle of sections of the graph with the selected regular regime. Under established structural and technological parameters, process intensification can be achieved at the expense of regime parameters (frequency and amplitude of oscillations of the vibration transport system). The combined effect of these parameters is supplied by the so-called intensity oscillations of the product of amplitude and frequency.
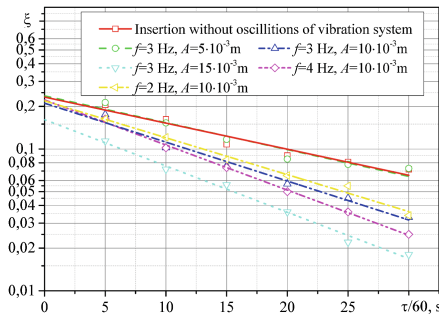

Fig. 4. Experimental curves of the kinetics of dry substance extraction from beet raw material with the release of the regular regime of the process.

The results of studies on the influence that the oscillation intensity of the transport system has on the external mass exchange for beet raw materials are shown in Fig. 5.
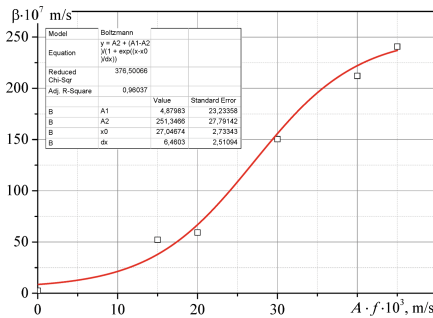

Fig. 5. Influence of oscillation intensity of the vibration transport system on external mass exchange during the extraction of sugar beet ($B = 300$ kg/m^3).

As the intensity of oscillations increases, the activation of the interphase surface increases as a result of reducing the conditions of screening of raw material particles among themselves. This phenomenon was taken into account by establishing the activity coefficient of the surface of a solid phase. Thus, according to the standard method adopted by Lysianskyi, when determining the coefficient of molecular diffusion of the raw material, conditions for the removal of the external diffusion resistance were created, whereas during a particular process that occurs directly in the apparatus, only a part of it takes part. Therefore, in the first case, the calculated diffusion coefficient is more important. That is, the coefficient of surface activity f_s can be represented as a ratio of coefficients D_t/D_r, where D_t, D_r—are respectively the coefficient of molecular diffusion of a substance tissue in the absence of a screening effect, and in the real process. The generalization of these studies is presented in Fig. 6. The character of the development of the curve coincides with the previous graph. That is, 100% removal of screening is achieved at the values of the mass return coefficient of about 225×10^{-7} m/s, which corresponds to the intensity of vibration system oscillations of 40×10^{-3} m/s.
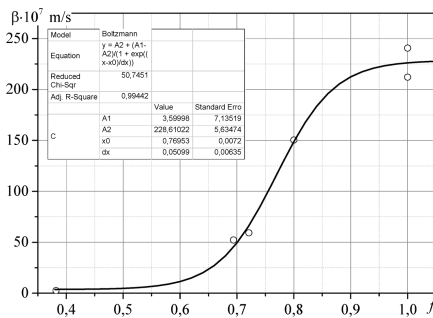

Fig. 6. Dependence of the coefficient of mass return on the degree of surface activity of beet raw material.

The generalized results of the study on the mass exchange characteristics of the vibroexctractor are shown in Fig. 7, where $\mathrm{Nu}_D = \beta_{ex} \cdot d_e / f_s \cdot D_b$—Nusselt diffusion criterion; $\mathrm{Re} = \overline{w}_L d_e / v_b$—an effective Reynolds criterion that takes the conditions of the screening of particle surface into account; $d_e = 2R_e$—equivalent diameter of the solid particles; v_b—kinematic viscosity of a boundary pellicle on the surface of the particle; D_b—dissolution coefficient of a substance; $\mathrm{Pr}_D = v_b / D_b$—Prandtl diffusion criterion. According to the presented graphic dependence, it can be argued that the most effective regime of vibroextractor operation (transition of the system to the fluidized state) comes at $\mathrm{Re}_e > 2300$, and the parameters of this regime should be considered preferable.
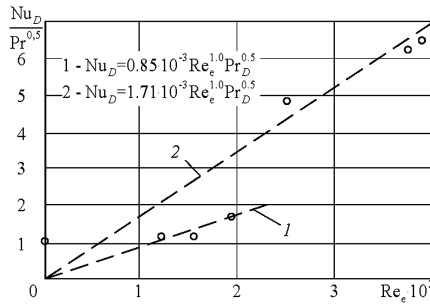

Fig. 7. Generalization of experimental data on the study of mass exchange characteristics of the vibroextractor.

4.3   Analytical Study of Mass Transfer with Continuous Vibration Extraction from Plant Raw Materials

Wide industrial use of new vibroextraction equipment requires theoretical substantiation of the features of the mass transfer mechanism at all its scale levels and the establishment of a reasonable relation between the constructive and technological parameters of the process within the given technological boundaries. Given the mechanism of countercurrent phase separation for the description of kinetics, it is expedient to consider the following equation of convective diffusion, taking into account the features of mass transfer of substance:

$$\frac{\partial m_1(x,t)}{\partial t} = D \frac{\partial^2 m_1(x,t)}{\partial x^2} - \upsilon \frac{\partial m_1(x,t)}{\partial x} + F(x,t), \qquad (1)$$

where $F(x,t) = k(m^*(x) - m_1(x,t))$; $m_1(x,t)$, $m^*(x)$—respectively, the variable in time and length of mass of the target component in the extractant and its equilibrium value in each cell of the apparatus; t—time of the process; x—length coordinate L of the working part of the apparatus; υ—extractant flow speed in the working area of the apparatus; k—coefficient of mass return; D—generalized diffusion coefficient of a substance. Thus, the first product of Eq. (1) describes the transfer of the target component in the tissue of the raw material at the molecular level, and also turbulent

diffusion on the phase contact surface; the second product is the convective transfer along the length of the apparatus, and the third—the density of external sources during convective diffusion in the zone of vibration mixing and in the formation zone of a layer of raw materials (accumulative component). Taking into account the boundary conditions:

- for the zone of extractant feeding, the balance of the substance will look like:

$$D\partial m_1(x,t)/\partial x = \upsilon(m_1(x,t) - \overline{m}_1(t)) \text{ at } x = 0, \tag{2}$$

where $m_1(x,t) - \overline{m}_1(t)$—concentration difference which determines the flow of the substance at the entrance to the apparatus and the substance concentration entering the apparatus with the extractant. Then, at the exit of the apparatus, for the flow of the substance

$$\text{at } x = L \quad \partial m_1(x,t)/\partial x = 0 \tag{3}$$

The initial condition for the boundary problem (1)–(3) will look:

$$m_1(x,t_0) = m_1^0(x), \ 0 < x < L. \tag{4}$$

where $m_1^0(x) = 0$—initial distribution of the substance concentration in the apparatus. In this case $\overline{m}_1(t) = 0$; since the extractant in the apparatus is fed without the contents of the target component. If, at a certain time, the amount of substance in the extractant $m_1(x, t)$ and in a solid phase $m_2(x, t)$ in the relevant section of the device is constant, then for all $t \geq 0$ we will have

$$m_1(x,t_0) + m_2(x,t_0) = m_1^0(x) + m_2^0(x), \tag{5}$$

where $m_1^0(x), m_2^0(x)$—respectively, the amount of substance in the liquid and solid phase at the beginning of the process.

Going to integration for the time limit from 0 to t and for the spatial coordinate from 0 to L, taking into account the change $\lim\limits_{x\to\infty} m_1(x,t) = m^*(x)$ and $\lim\limits_{x\to\infty} m_2(x,t) = m^*(x)$, where $m^*(x)$—the equilibrium concentration of the target component throughout the length of the apparatus, and then using the material balance equation in the integral form and using the method of distribution of variables, the solution of model (1)–(3) will have an analytical form:

$$m_1(x,t) = \int_0^L G(x,\zeta,t)m_1^0(\zeta)d\zeta + \int_0^t \int_0^L G(x,\zeta,t-\tau)km^*(\zeta)d\zeta\,d\tau + \upsilon \int_0^t G(x,\zeta,t-\tau)\overline{m}_1(\tau)d\tau,$$

$$\tag{6}$$

where ζ, τ—variable of integration over spatial coordinates and in the time coordinate, respectively; $G(x, \zeta, t) = e^{\left(\upsilon(x-\zeta)/(2D)-\left(k+\upsilon^2/(4D)\right)t\right)} \sum_{n=1}^{\infty} J_n(\zeta)e^{-D\mu_n^2 t}/B_n$—Green's function, in which $J_n(x) = \cos(\mu_n x) + \upsilon \sin(\mu_n x)/(2D\mu_n)$ and $B_n = L/2 + \upsilon$ $(1+L\upsilon/(4D))/(2D\mu_n^2)$

– functions and numerical coefficients of an infinite series, respectively; μ_n—positive roots of the characteristic (transcendental) equation;

$$\mathrm{tg}(\mu L)/\mu = 4D\upsilon/\left(4D^2\mu^2 - \upsilon^2\right). \tag{7}$$

After completing the change of variables $\lambda = \mu L$ (λ—dimensionless value), transform the last equation to form:

$$\mathrm{tg}\lambda/\lambda = 4D\alpha/\left(4D^2\lambda^2 - \alpha^2\right) \text{ or } \mathrm{tg}\lambda/\lambda = 4D\upsilon L/\left(4D^2\lambda^2 - \upsilon^2 L^2\right), \tag{8}$$

where $\alpha = \upsilon L/D$—Peclet diffusion criterion.

The accumulation component $F(x, t)$ can be refined by a function that summarizes the expression (1).

Note that the random variable $m_1(x, t)$ may correspond to a certain statistical distribution, for example Gaussian.

Given the constancy of the equilibrium mass of the substance in each i-cell of the apparatus, for the entire apparatus the function will have the form:

$$F(x, t) = (m^*(x) - m_1(x, t))g(x). \tag{9}$$

In this equation, the second multiplier is a function $g(x) = \sum_{i=1}^{n} K_i e^{-\overline{\alpha}(x-x_i)^2}$, where n—number of cells; i—cell number, which takes into account the mass transfer of the substance from the solid phase to the liquid in the length of the apparatus and has a distribution depicted in Fig. 8. Here $\alpha = \alpha(f, A)$—parameter which characterizes the degree of mass transfer in i-th cell; f, A—respectively, the frequency and amplitude of oscillations of the vibration transport system; n—number of cells; K_i—mass transfer coefficient for i-th cell; x_i—coordinate of i-th cell.

If the coefficient of mass return K_i is constant for each cell and is equal to K, then

$$g(x) = \sum_{i=1}^{n} K_i e^{-\overline{\alpha}(x-x_i)^2} = K\varphi(x), \tag{10}$$

In this equation, the function $\varphi(x)$ has the content of the accumulation component of the model (1).

It should also be noted that the density of the distribution of the parameter as the density of the sources of the extractive substance in a certain regime of apparatus operation depends on the intensity of oscillations of the vibration transport system determined by the output amplitude and frequency.
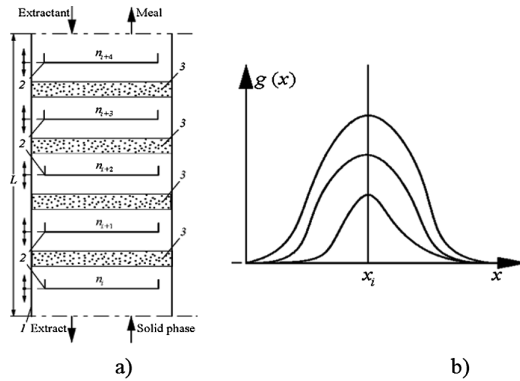
Fig. 8. Density of the extraction substance distribution over the length of the apparatus: **a** Scheme of accumulation of the solid phase over the length of the apparatus: (1) body; (2) vibration plate; (3) accumulated solid phase layer; **b** Illustration of the change density of the extractive substance in i-th cell.

$$\overline{\alpha} = \overline{\alpha}(f, A). \tag{11}$$

That is, we can assume that $\overline{\alpha} = MAlf^m$, where M—coefficient of proportionality; l, m—some valid numerical values of this degree of dependence. At $l = 1$, $m = 1$,

$$\overline{\alpha} = MAf. \tag{12}$$

Consequently, an increase in the parameter $\overline{\alpha}$ leads to an increase in the density of the Gaussian-like distribution. Regarding the apparatus, this means that the intensity of mass transfer increases with the increase in $\overline{\alpha}$, that is, with increasing dissipation of energy in the zone of vibration mixing.

Thus, the obtained results may be useful at the design stage of vibroextraction equipment and in solving optimization problems of mass transfer at the level of molecular and convective diffusion, taking into account the external sources of accumulation of the target component in the extractant in the zone of vibration mixing.

5 Conclusion

During vibroextraction, the surface of the phase contact is renewed due to the regime parameters of the process (frequency and amplitude of oscillations of the vibration transport system). The amplitude of oscillations of the vibration transport system within the range $(10–15) \times 10^3$ m with a frequency of 2–4 Hz should be considered to be the rational regime parameters sufficient for the effective external mass exchange and the renewal of the contact surface of phases with a low level of longitudinal mixing.

The density of the substance source, which characterizes the density of the concentration change of the target component, or the accumulation of the extractive substance in the extractant, taking into account the influence of technological factors on

the process (hydromodule, temperature, properties of raw materials, extractants, constructive parameters, etc.), primarily depends on the changes in the parameters of oscillations of the vibration transport system amplitude A and oscillation frequency f.

Technological and economic characteristics of vibroextractors of continuous action make them competitive on the domestic and world market of extraction equipment. The developed method can be realized in processing industries to ensure non-waste and in-depth processing of plant raw materials: in brewery—for the more complete removal of bitter substances during the chilling of wort and processing of malt germs; in wine-making and canning—for the extraction of coloring material from fruits and berries, and also for the processing of spicy and aromatic plant raw materials for the production of beverages; in the sugar industry—for the processing of non-standard beet-mass (crushed and beet tails); in the pharmaceutical sector—for the extraction of biologically active substances from medicinal plants, and more.

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