PRINCIPLES OF VIBROEXTRACTION AND PROSPECTS OF ITS APPLICATION IN FOOD PRODUCTION INDUSTRY

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Abstract: In the present work, we present results of investigations of the intensifying action of low-frequency mechanical vibrations on the extraction process of desired components from vegetable raw materials under conditions of continuous vibration extraction. Mathematical models that can be used for the scaling and the embodiment of vibratory extraction equipment have been developed. We have also developed a new mathematical model for evaluating the level of longitudinal mixing in continuous vibratory extraction. For industry, we propose a new design of a vibratory extractor with a transporter, which provides efficient separation of phases under the conditions of counterflow vibratory extraction of desired components from vegetable raw materials.

Keywords: Vibratory extraction, mathematical modeling, intensification, mass transfer, vegetable raw material, hydrodynamic flow

Introduction

The rise in the production and the increase in its efficiency in all the processing industries depend to a large degree on not only resources of raw materials, but also the completeness of extraction of valuable components from it.

For the most material-intensive food industries such as the sugar, oil and fat, food-canning, wine, alcoholic beverage, starch, molasses, and pharmaceutical industry, in which one million tons of raw materials of vegetable, root, fruit, and berry origin are annually processed, these problems are particularly urgent.

As a rule, vegetable raw materials or their mass prepared for extraction do not have a sufficiently high natural porosity for efficient counterflow extraction, are transported badly, and can be densified. As a result, the practical problem of providing conditions for the optimal realization of the extraction process by traditional methods is complicated, on the one hand, by the aforementioned and other properties of the raw material and, on the other hand, by the manufacturing capabilities and the design possibilities of the existing extraction equipment.

In connection with the foregoing, one of the most efficient methods of the intensification of the extraction process consists in using intensive hydrodynamic regimes. Among known apparatuses operated in these regimes, vibratory extractors are the most promising. They are distinguished by the high relative interaction rate of phases, manufacturability, and ease of operation. Apparatuses of this type can operate in the regime of intensive alternating turbulization of a flow of a mixture of interacting phases. This surface activation, which leads to an abrupt increase in the motive force and a decrease in the diffusion resistance of the process, is provided by turbulizing mixture flows generated by vibratory mixing devices located in the working volume of the apparatus.

1. Design features of the continuous vibratory extractor

Vibratory extraction is a relatively new technological process; its general theory is complex and still in its early stages of development. In recent years, in the Department of Processes and Apparatuses of Food Production of the Kyiv National University of Food Technologies, deeper notions of the kinetics and the mechanism of vibratory counterflow extraction have been acquired. As a result, a new extractor design with a vibratory transport system has been developed and implemented (Fig.1) [1]. The apparatus consists of a cylindrical column (1) with a U–shaped charging device (2), a vibratory transporter with transverse partitions (plates) (3) (Fig. 2) that are fixed in turn on vertical rods (4) and (5) and execute harmonic vibrations shifted by a one-half period. A vibratory drive (9) with a crank mechanism provides the fixed amplitude and frequency of motion of rods. A scraper (6) with a tray (7) serve for discharging raw materials subjected to extraction. A sprinkler (10) located above the upper plate serves for feeding the extractant into the apparatus.

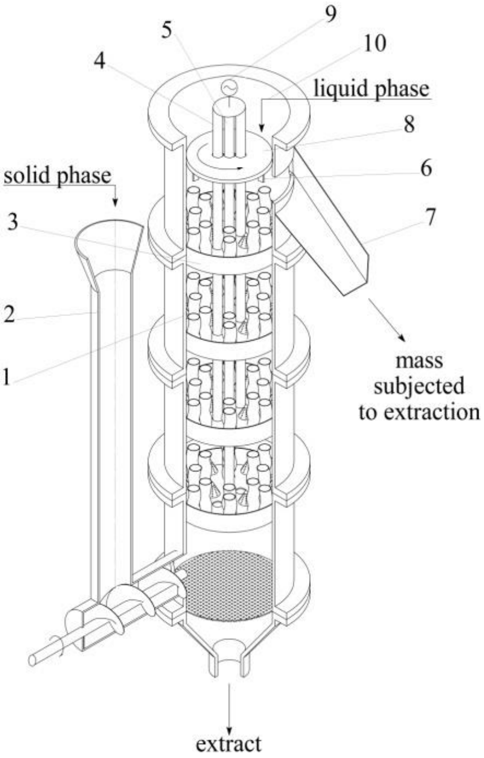

Fig. 1. Scheme of a vibratory extractor:
1. apparatus body; 2. charging device;
3. vibratory transport plate; 4. rod; 5. rod;
6. scraper; 7. tray; 8. discharging mechanism;
9. vibratory drive; 10. sprinkler.

The principle of operation of the apparatus and the mechanism of counterflow vibratory transportation was fairly completely described in [2].

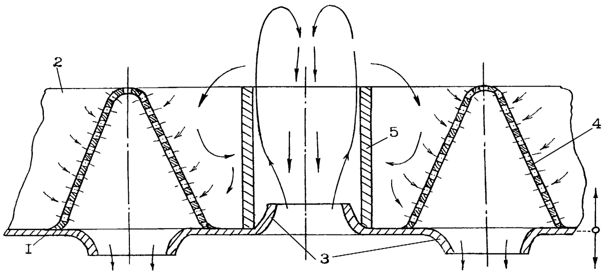

Fig. 2. Vibratory transport plate:
1. disk with nozzles; 2. edge; 3. nozzle;
4. filtering element; 5. pipe.

Turbulent pulsing flows generated by vibrating elements (nozzles) create optimal hydrodynamic conditions for counterflow mass exchange due to intensive micromixing in the cross-section of the working volume of the apparatus with minimum longitudinal mass exchange. Under extremely high turbulization in the zone of the plate, the developed large interface provides conditions for intensive mass exchange. At the same time, the residence times of particles in the working volume of the apparatus are almost equal. This fact was substantiated by experimental data on the determination of the level of longitudinal mixing from the curves of the response to the introduction of a tracer agent (C-curves, on the basis of the diffusion model) [3]. For instance, the coefficients of longitudinal mixing D_L computed from the obtained data lie in the range from $1.32 \cdot 10^{-4}$ to $2.02 \cdot 10^{-4}$, which is permissible for extraction apparatuses [4].

2. Results of investigation of the motion of pulsating flows

The results of experimental investigations of the distance of action of pulsating flows are generalized by the relation [5]

$$Str = c\left[d_n\varepsilon/2\grave{A}(1-\varepsilon)\right]^{0,85} \cdot \mathrm{Re}_p^m, \tag{1}$$

where $Str = L_0\varepsilon / 2A(1-\varepsilon)$ is the Strouhal number (the ratio of the time it takes for the flow front to traverse a distance L_0 at a velocity w_0 to the period of vibration of the plate); L_0 is the distance from the vibrating plate, which corresponds to a decrease in the velocity of the flow by an order; $\mathrm{Re}_p = 4A^2 f(1-\varepsilon)/\varepsilon\nu$ is the Reynolds number of the pulsating flow; ν is the kinematic viscosity of water; c is a constant that depends on the geometry of the nozzle, m is an exponent equal to 1.05 in a laminar regime ($\mathrm{Re}_p < 2.3 \cdot 10^3$) and to 1.76 in a transient regime ($2.3 \cdot 10^3 < \mathrm{Re}_p < 5 \cdot 10^3$); A and f are, respectively, the amplitude and the frequency of vibrations of the vibratory transport system; ε is the free cross-sectional area of the plate (ε ranges from 0.055 to 0.142); d_n is the diameter of the nozzle.

The value of L_0, which is determining for the calculation and optimization of operation of vibratory extractors, can be calculated from the obtained relations.

Designs of vibratory transporters were investigated and recommended on the basis of the fundamental notions of the hydrodynamics of turbulent pulsating flows. It was established that the pulsating flow generated by the transport nozzles (4 in Fig. 2) consists of individual nonstationary vortex rings, which follow one another in space and time [6].

The results of investigations of pulsating flows in the turbulent regime of motion were generalized in the form of a dependence of the relative velocity w_L / w_0 [7] on the functional space characteristic $\eta_f = l / l_f$ (Fig. 3), where w_L is the mean integral velocity of the pulsating flow over the cross-section during the period of vibrations; $w_0 = (2fA \cdot (1-\varepsilon)) / \varepsilon$ is the initial velocity of the pulsating flow; $l = L / r_n$ is the relative distance; L is the given distance from the partition; r_n is the radius of the nozzle; l_f is the value of l for which $w_L / w_0 = e^{-1}$; e is the base of natural logarithms.

In these functional space–time coordinates (Fig. 3), the whole data array was generalized for η_f smaller than its critical value $(\eta)_{fK} = (0{,}1 \cdot e \cdot \ln 10) / (1-e^{0.5})^{2/3} = 1{,}1656538$ by the well-known Schlichting formula [8] for the universal profile of velocities in turbulent far wakes

$$w_L / w_0 = \left[1 - \left((\eta_f \cdot l_f) / l_0\right)^{3/2}\right]^2, \tag{2}$$

and, for $\eta_f > (\eta)_{fK}$, by the relation

$$(\eta_f)^3 \left(\frac{w_L}{w_0}\right)^2 = C_T, \tag{3}$$

where

$$C_T = (\eta)_{fK}^{3}\left[1-(\eta_f)_K^{3/2}\left(1-e^{-0,5}\right)\right]^4 = 0,10286 \qquad (4)$$

is a fundamental constant; $l_0 = L_0 / r_n$ is the relative limit distance that the turbulent pulsating flow traverses, and L_o is its absolute value.

The theoretical value is $\left(l_f / l_0\right)_T = \left(1-e^{-0.5}\right)^{2/3} = 0.53695838$. After computing the experimental value of l_f from the dependence of $\left(w_L / w_0\right)$ on l, we can calculate L_K and w_L, which are necessary in the design of vibratory extractors. Thus, according to the foregoing, the possibility of using the fundamental regularities for the computation of the hydrodynamics of turbulent pulsating flows was established.

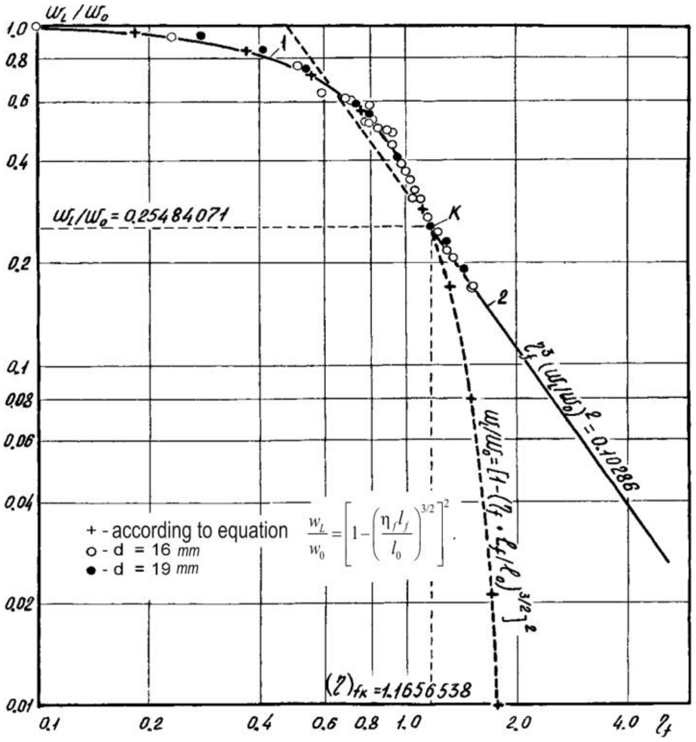

Fig. 3. Generalization of experimental data on the investigation of the hydrodynamics of turbulent pulsating flows by the dimensionless profile of the relative velocity.
(1) by the Schlichting equation; (2) by Eq. (2).

3. Investigation of mass transfer in vibratory extraction

The influence of design and regime parameters that determine the rate of the interphase interaction on the kinetic coefficients in extraction from sugar beet cossette was investigated [9]. Under laboratory conditions, we changed the frequency of vibrations of the vibratory transport system from 2 to 4 Hz, the amplitude from $5 \cdot 10^{-3}$to $15 \cdot 10^{-3}$ m, the ratio of the mass of the solid phase to the mass of the liquid phase from 0.25 to 0.85, and maintained the temperature of the juice–cossette mixture in the range 340–350 K.

Generalized results of the investigation of the mass-transfer characteristics of the vibratory extractor are presented in Fig. 4, where $\mathrm{Nu}_d = \beta_{exp} \cdot d_e / f_f D_f$ is the diffusion Nusselt number; $\mathrm{Re} = \overline{w_L}\, d_e / \nu_f$ is the effective Reynolds number, which takes into account the conditions of shielding of the surface of particles, $d_e = 2R_e$ is the equivalent diameter of a hard particles, v_f is the kinematic viscosity of the boundary film on the surface of particles, D_f is the diffusion coefficient of the matter solution, and $\mathrm{Pr}_d = v_f / D_f$ is the diffusion Prandtl number.

On the basis of the shown graphic dependence, we can state that, at $\mathrm{Re}_e > 2300$, the vibratory extractor passes to the most efficient operating regime (into the state of a pseudo-liquefied layer), and it is reasonable to believe that precisely the parameters of this regime are dominant.

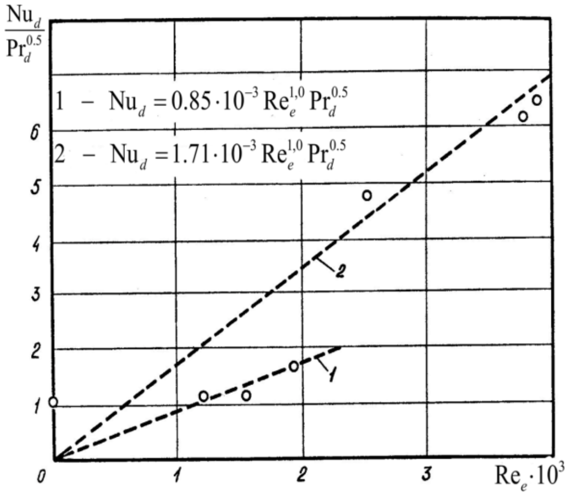

Fig. 4. Generalization of experimental data on mass-transfer

4. Investigation of the transport capability of the vibratory extractor

An investigation of the capability of the working elements of the apparatus to transport vegetable raw materials with different geometry and physical properties was performed on the following systems: husks of grapes–water, hop–water, ground beet mass–water, oak crumbs–water.

Two mechanisms of counterflow separation of interacting phases were investigated. The first mechanism is due to the difference in the motive forces that arises in the case of alternating directions of motion of the medium through nozzles with different hydraulic resistances, and the second (sedimentation) mechanism is based on the presence of organized flow circuits, which are generated in nozzle holes. The flow circuits are closed and localized at a certain distance from the partition in the direction of transport, whereas on the opposite side of the plate, they are open (Fig. 2).

The action of these mechanisms is provided by optimal geometric ratios of transporting elements, namely, the ratio of the height of the pipe to its diameters ranges H/D ranges from 1.5 to 3, and the ratio of the diameter of the pipe to the diameter of the nozzle D/d_n ranges from 1.5 to 2.5.

Conclusion

The application of low-frequency mechanical vibrations to interacting media through vibratory transporters is an efficient method for the intensification of an extraction process, favors a decrease in the external diffusion resistance, and increases the active surface of mass transfer to about 100%.

It has been established that the activation of the interface in the process of vibratory extraction from vegetable raw materials is provided by the generation of pulsating turbulent flows by the elements of vibratory transporters, which produce simultaneous processes of mixing and counterflow separation of phases. Low-frequency mechanical vibrations with a frequency to 4 Hz do not provide substantial longitudinal mixing.

The developed mathematical models of the structure of flows and mass exchange can serve as a base for the solution of optimization problems.

We have established optimal design and operating parameters of the vibratory transporter, which provide efficient external mass exchange under conditions of extraction of desired components from hop raw materials by water and have the highest transport capability with small longitudinal mixing. These are amplitude of vibration *A* of 10^{-2} to $15\cdot10^{-3}$ m and a frequency of vibrations *f* of 2 to 4 Hz.

The use of vibratory extractors is most promising in the case where traditional extraction methods are inefficient, namely, for solid fine-fraction vegetable raw material–liquid systems.

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