Substantiation of Energy Parameters of a Continuous-Action Vibroextractor for a Solid-Liquid System

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Abstract. The results of studies on energy consumption for the process of extracting target components with continuous vibration extraction in a solid-liquid system with a small difference in phase densities are presented. The influence of low-frequency mechanical oscillations on energy consumption is substantiated and regularities of their change from the mode parameters of the process are established. It is established that the power required to perform vibration mixing is determined by the fictitious force in the oscillatory motion and the resistance created by the viscous friction of the mixing device in the working environment. Taking into account the fictitious component of the vibrating mixing system, the equation of total energy consumption for the continuous vibration extraction process is obtained. For the interpretation of the obtained experimental dependencies, the energy consumption by the vibration mixing devices was calculated. It has been shown that vibration mixing allows for the efficient use of the energy invested in a unit of work volume, evenly distributing it in the cross-section of the apparatus.

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

1 Introduction

Development of a new high-efficiency solid-phase extraction apparatus for systems with a small difference in phase densities fully reflects one of the main topical directions of improving the production base of processing industries and orientates to the search for new energy-saving methods for the intensification of technological processes. This is especially true of the problem of the most complete extraction of the target components from plant raw materials, including waste recycling. Thus, apparatus that use the traditional principles of the organization of the counterflow phase for the processing of small fractional raw materials in the food, pharmaceutical, and chemical industries were not workable or ineffective due to the effect of shielding particles between themselves, resulting from the low porosity of the compressed layer of the solid phase by working transport devices. For these purposes, the most promising was

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the apparatus based on the use of low-frequency mechanical oscillations with the new principle of counterflow phase separation with the help of vibration transport plates of special design, which do not cause compression and provide proper porosity of the raw material layer, regardless of the fraction of solids [1–6].

At the same time, vibration extraction is a relatively new technological process. The widespread industrial use of this type of apparatus is hampered by a number of unexplained important issues related to the theory and practice of the process, including the insufficient study of energy consumption in the process.

Thus, despite the advantages and interest of industry in vibration extraction technologies for solid-liquid systems with small phase density differences, purposeful design and optimization of the vibration extractor mode parameters are impossible without deepening the fundamental ideas about their energy-consuming characteristics. Therefore, the task was to substantiate the influence of low-frequency mechanical oscillations generated by the drive system on the energy consumption in the conditions of vibration extraction of raw materials and to establish the regularities of its change depending on the design and mode parameters of the apparatus.

2 Literature Review

Regarding the comparison of the energy consumption of the process by mixing in other ways, such as those used in traditional extractors - mechanical rotation method, the following should be noted. Many years of experience in the application and research of pulsation and vibration mass transfer equipment in the chemical industry by scientists S.M. Karpacheva, I.Ya. Gorodetsky, A.A. Vasin, V.M. Olevsky [1] and their employees proved that the energy consumption of pulsation and vibration of the working environment per unit of production are than other devices with additional power supply or close to them [2]. This is explained by the fact that the pulsator or vibrator motor consumes 0.25–1 kW and is not noticeable for large devices [7]. In addition, in this case, a continuous vibration extraction uses a balanced vibration system with a relatively small amplitude and oscillation frequency. Consequently, the continuous extraction equipment created as a result of the conducted research is competitive in comparison with other, similarly used equipment, in all indicators of its work [1].

3 Research Methodology

Research methods include experimental and analytical modeling. The calculated equations of energy consumption during vibration extraction were obtained by methods based on classical provisions of the theory of mathematical modeling.

The rotation speed of the motor shaft and the oscillations of the vibration transport system within 10 Hz were carried out by an autotransformer. The power required to perform work during vibration mixing was determined by the electrical method by the difference of power in the conditions of working (with the working environment) and idle (without working environment) movements of the vibrating system and taking into account the losses on the active resistance of the motor drive by the equation

$$N = N_w - N_i - \left(I_w^2 - I_i^2\right)R, \tag{1}$$

where N—total power required to perform mixing work, W; I_w, N_w—respectively the electric current and power required to perform the work during the work movements, A, W; I_i, N_i—respectively the electric current and power required to perform idle motions, A, W; R—active resistance of the drive motor of the apparatus, Ohm.

Changing the oscillation parameters of the vibrating mixing system, the dependence of the specific power during vibroextraction on the Reynolds criterion was established.

Experimental data processing and calculations were performed with the use of modern integrated systems MathCAD, OriginPro 8.6 and others.

4 Results

The advantages of vibration mixing in combination with vibration transportation are achieved by the improved realization of pulsating flows of the working environment in the flow speed form around the contact surface of the phases. In particular, vibration mixing can increase the capacity that effectively fits into the unit of the mixing volume, evenly distributing it in the cross-section of the apparatus of interest in creating a compact high-power single extraction apparatus. Therefore, determining the efficiency of process-intensifying devices needs to compare the process acceleration with the energy consumption of that intensification. It is known that mixing energy is expended on overcoming the fictitious forces arising from the reciprocating movement of moving parts; for lifting plates and rods, parts and moving parts crank rod mechanism, etc.

4.1 Design Features of the Continuous Vibroextractor

The studies were performed on a pilot vibration extractor of continuous action, made according to the scheme in Fig. 1. [3, 4]. The oscillation amplitude varied within (5…15)·10^{-3} m, frequency – (1…10) Hz. The apparatus has a vertical housing 1 with a diameter of 0.3 m, a height of 1.5 m, with devices for input and output of phases. In the working volume of the device, there is a mechanical balanced system of two vertical rods 2 with fixed vibrating plates 3 attached to them. The oscillatory counter-motion of this vibration system with a given frequency and amplitude is provided by vibration drive 5. The type of plates installed in the extractor depends on the type of raw material.

As an example, in Fig. 2. a transport-separation plate is presented [3, 4]. The function of the plate is realized by the difference of hydraulic resistances of the working environment flow through the conical multi-directional transport elements 1 included in the nozzles, as shown in Fig. 2 [8].

The optimum ratio of the geometrical parameters of the transport 1 and filter 2 elements creates the porosity of the solid phase layer, the proper flow rate of the surface of the extractant with a low level of longitudinal mixing in the apparatus.

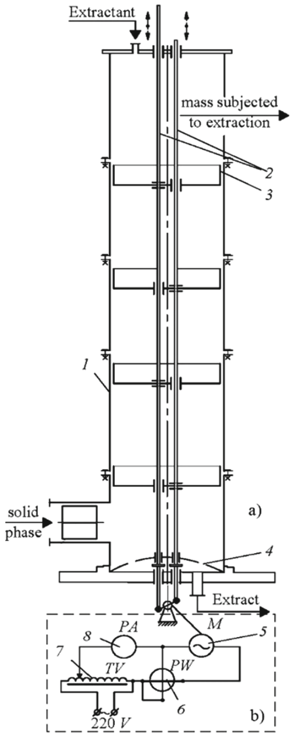

Fig. 1. a) scheme of a continuous vibration extractor; b) scheme of energy consumption measurements: (1) apparatus body; (2) rods; (3) vibratory transport plate; (4) filter; (5) vibratory drive; (6) wattmeter; (7) autotransformer; (8) ammeter.

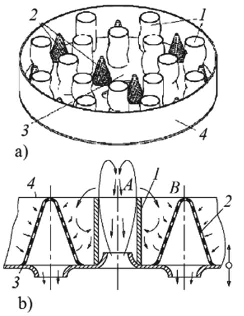

Fig. 2. Transport-separation plate: a) general view of the plate; b) phase separation scheme: (1) pipes; (2) filter elements; (3) plate; (4) board.

The fine fractional solid phase is fed into the apparatus under the last lower plate and in the form of a meal is discharged from the apparatus at the level of the upper one. The extractant is fed to the first top plate and in the extract, the form is removed through filter 2. The oscillation energy of the driven system with controlled frequencies and amplitudes through the vibration transport devices is realized in the working volume of the apparatus.

4.2 Mathematical Description of Energy Consumption During Vibroextraction

It should be assumed that energy is spent on vibration extraction to overcome the fictitious forces arising from the reciprocating movement of the moving parts of the apparatus, to move the vibration transport system up and down and to overcome the resistance of its friction forces to the working environment. Assuming that the vibration transport system is a fixed set of hydraulic resistance through which the flow of the working environment moves alternately in one direction and the other, the total energy consumption for the process can be determined by the equation:

$$N = n(N' + N'')/2 + nN_g + N_I, \tag{2}$$

where n — the number of vibratory plates; N′, N″, Ng, NI—accordingly the energy consumption for overcoming hydraulic resistance when moving the working medium up and down through the transport and filter elements of the plates, through the lateral gap between the plate and the apparatus body and to compensate for the fictitious forces of the moving structural elements of the apparatus. It should be noted that the vibration transport system (a system of two rods with the alternate fixing of plates on them) leads to movement in the counter-phase level by mass of the subsystem, and therefore - provides minimal energy consumption for the movement of these masses.

Appropriate equations can be used to calculate a certain component of energy consumption, taking into account the design and operating parameters of the apparatus [9–11]. For example, to determine the energy consumption to overcome the hydraulic resistance of a plate when it moves up N' — down N'':

$$N' = n_1 N_1' + n_2 N_2', \tag{3}$$

$$N'' = n_1 N_1'' + n_2 N_2'', \tag{4}$$

where n_1, n_2 — respectively, the number of transport and filter elements on one plate; N_1', N_2', N_1'', N_2''—respectively, the energy consumption to overcome the hydraulic resistance of one transport and one filter element when moving the plate up and down.

That is, a generalized form of the equation for the calculation of these components will look like:

$$N_1^{\prime(\prime\prime)} = Q_1^{\prime(\prime\prime)} \cdot \Delta p_1^{\prime(\prime\prime)} = w_0 \cdot \Delta p_1^{\prime(\prime\prime)} \cdot \pi d_{e_i}^2 \Big/ 4, \tag{5}$$

where $\Delta p_i^{\prime(\prime\prime)} = \rho w_0^2 \left(\lambda_i H_i / d_{e_i} \xi_{in_i} + \xi_{p_i} + \xi_{out_i}\right)/2$—pressure drop on both sides of the plate; $\xi_{in_i}, \xi_{p_i}, \xi_{out_i}$—coefficients of local hydraulic resistance, respectively, at the inlet of the mixture flow into the plate elements, at its instantaneous expansion and the outlet of the plate elements; $w_0 = 2Af(1-\varepsilon)/\varepsilon$—the initial middle integral velocity of pulsating flows during the period of oscillations generated by the plate elements, which ensure the transportation of the working environment through a certain plate element; A, f—respectively, the amplitude and frequency of oscillation; ε—relative total free cross-section of the plate; $Q_1^{\prime(\prime\prime)}$—volumetric flow rate of the working environment through the plate element; H, de—respectively, the length of the friction surface of the element through which the working mixture moves and the equivalent diameter of the plate element; λ—the coefficient of friction between the environment and the surface of the plate element.

In Eq. (5), due to the small value of the ratio $\lambda_i H_i / d_{e_i}$, it will be logical to consider it only in the case of calculating the energy consumption when flowing the working environment through a transport element with a branch pipe height H_p and energy consumption for overcoming hydraulic resistance when moving the working environment through the peripheral gap between the plate with the board height H_b and the apparatus body.

Therefore, to account for the inertial component, let us consider the driving system of the vibroextractor, whose kinematic scheme is shown in Fig. 3. Note that the widespread use of connecting rod electromechanical drive mechanisms has been obtained to create vibrating oscillations of the nozzles. In such a drive the connecting rod is the link between the crank and the rod [12–15].

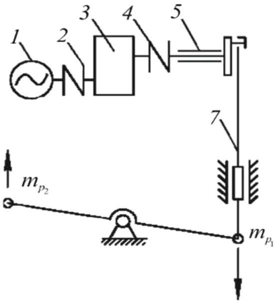

Fig. 3. Scheme of electromechanical crank drive: (1) electric motor; (2), (4) couplings; (3) reducer; (5) eccentric; (6) connecting rod; (7) rod; $mp_1 = mp_2$—respectively, the mass of vibration transport systems moving in counter-phase

The energy consumed by the drive of the vibrating apparatus can be represented in the form of components: static power spent on lifting the moving parts of the plates (nozzles, rods, parts of the crank mechanism, fasteners); the energy expended to overcome fictitious forces arising from the reciprocating movement of moving parts; the energy consumed to overcome the friction forces of the working devices (plates) by interaction with the working environment in the apparatus, and the friction forces in the elements of the drive parts. Respectively, the force consisting of similar components acts on the apparatus stock. Knowledge of the required power and force acting on the stock is necessary for the correct selection of energy equipment and to calculate the strength of the elements of extraction equipment with oscillating effects in the working volume of the apparatus [1].

So, by analogy [1] the fictitious force of the vibrating mixing system, that is, the inertial component of the energy consumption N_I, must take into account the mass of the plate, stock, the corresponding fasteners of the plates and pushing force from the environment acting on the system immersed in the work environment:

$$P_I = \frac{m_s + m_l}{g \cdot \rho_s}(\rho_s - \rho_l) \cdot \frac{d^2S}{dt^2}, \tag{6}$$

where ρ_s—density of structural materials, kg/m^3; ρ_l—density of the working environment, kg/m^3; $d^2S/dt^2 = -2\pi^2 f^2 A \sin\beta$—acceleration of the moving system of the crank mechanism, moving at an angular speed $dS/dt = \pi A \cos\beta$ (see kinematic scheme in Fig. 3).

Then

$$P_I = \frac{m_s + m_l}{g \cdot \rho_s}(\rho_s - \rho_l) \cdot 2\pi^2 f^2 A \sin\beta. \tag{7}$$

Finally, given the above, we will have:

$$N = \frac{w_0 \pi d^2 n}{8} \cdot \sum P_1^{\prime(\prime\prime)} + N_g + \frac{m_s + m_l}{g \cdot \rho_s}(\rho_s - \rho_l) \cdot 2\pi^2 f^2 A \sin\beta. \tag{8}$$

where m_s, m_l—respectively, the mass of structural materials and the working environment moving the plate, kg; β—the angle of rotation of the crank mechanism, °; g—free-fall acceleration, m/s^2.

It should be noted that, for the vibration extractor of continuous action, the requirement of constructive execution of the vibration transport plate is to manufacture and install it in the apparatus body with a minimum gap around the periphery. Therefore, when calculating the energy consumption for such apparatus, it is possible to disregard the component N_g, the energy consumption for overcoming hydraulic resistance when moving the working environment up and down through the lateral gap at the periphery of the plate.

4.3 Investigation of the Influence of Regime Parameters of the Device on Energy Consumption

Investigation of energy consumption for continuous process in the system of kapron crumb – water was performed on the model of the vibrating extractor shown in Fig. 1-a according to the schematic diagram of electrical measurements Fig. 1-b. At the same time, the ratio of liquid and solid phases at a temperature of 293 °K varied from

0.25 to 0.85. The oscillation frequency of the vibration transport system varied within 1–10 Hz; the oscillation amplitude was fixed at values (5, 10, 15) · 10^{-3} m.

For interpretation of the obtained experimental data, the energy consumption by working devices for vibration mixing was calculated.

The results of the experiments were summarized in the form of dependencies of the specific consumption of consumed electricity on the process at different mode parameters of the apparatus operation from the Reynolds pulsation criterion in the coordinates $N/Q = \varphi(\mathrm{Re})$, where Q—volumetric performance of the apparatus in the solid phase, m^3/s (Fig. 4).

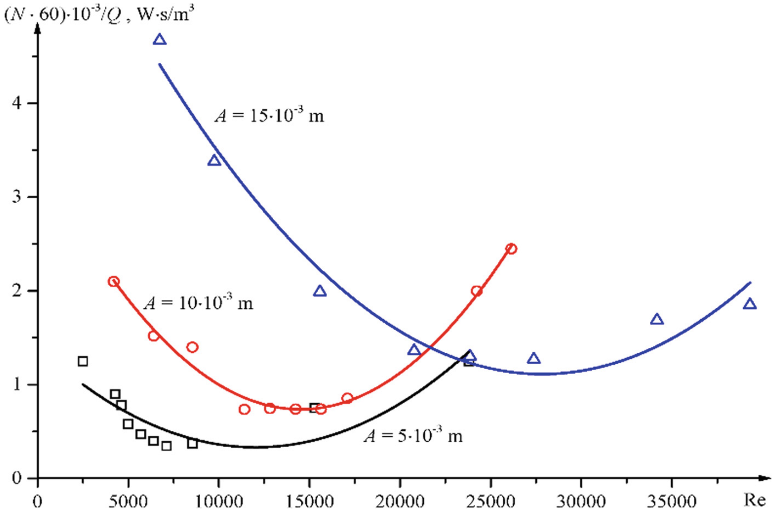

Fig. 4. The dependence of the specific electricity consumption on the oscillation intensity of the vibration transport system in the continuous process of vibration extraction.

The Reynolds pulsation criterion $\mathrm{Re}_p = w_0 d/v$ was calculated by the value of the initial middle integral and average cross-section of the transport element (nozzle) of the pulsating flow rate $w_0 = 2Af(1-\varepsilon)/\varepsilon$, where ε—the total cross-section, which is the ratio of the area of the plate holes and the gap along the periphery (in the area of the plate installation) to the cross-sectional area of the apparatus; A, f—respectively, the amplitude and frequency of vibration of the vibration transport system. That is $\mathrm{Re}_p = 4A^2 f(1-\varepsilon)/(v\varepsilon)$.

It is established that the oscillation amplitude of the vibration system has the most significant influence on energy consumption during transportation and phase separation. Also, the nature of the curves leads to the conclusion that the process can be optimized.

In other words, of the three given oscillation amplitudes, the most favorable is the amplitude 10 · 10^{-3} m. Also, the minimum energy consumption for all three graphs also determines the optimal oscillation frequency.

Thus, for amplitude $5 \cdot 10^{-3}$ m, the optimal oscillation intensity is 40 m/s, which corresponds to a frequency of 8 Hz; for amplitude $10 \cdot 10^{-3}$ m, the optimal oscillation intensity is—30 m/s at a frequency of 3 Hz; for amplitude $15 \cdot 10^{-3}$ m, the intensity is – 43 m/s at a frequency of 2.7 Hz.

The results of the experiments confirm that continuous counterflow vibration phase separation provides an increase in the amount of energy that is effectively invested in a unit of working volume - due to its uniform distribution in the cross-section of the apparatus.

5 Conclusions

The advantage of the vibration mixing method in the conditions of the process of solid-phase extraction in comparison with mixing by the currently most promising turbine stirrer is achieved due to the best mass transfer and energy realization of pulsating flows of the working environment.

The vibration mixing and the pulsating flows of the working environment generated in the holes of the transport elements create optimal hydrodynamic conditions for intensive mass transfer and contribute to the efficient investment of energy in the unit of the mixing volume, evenly distributing it in the cross-section of the apparatus of interest in the creation of a compact mass transfer apparatus of a single high power.

The power required to perform vibration mixing is determined by the fictitious force of the oscillating motion and the resistance created by the viscous friction of the mixing device in the viscous work environment.

The optimal mode parameters for a continuous process that ensure proper phase separation with low energy consumption are the amplitude of oscillations from 10 10^{-3} to $15 \cdot 10^{-3}$ m at a frequency of up to 4 Hz, depending on the properties of the solid phase.

The realization of the obtained results makes it possible to develop a method of engineering calculation of the energy characteristics of continuous vibration extraction in a solid-liquid system with a small difference of phase densities for the design of appropriate industrial equipment in the pharmaceutical, food and chemical industries.

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