ISSN 2306-8744 № 2 (121) 2026 Вібрації в техніці та технологіях

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УДК 621.927.5
DOI: 10.37128/2306-8744-2026-2-2

RESEARCH INTO DEWATERING PROCESSES OF WET DISPERSED MATERIALS UNDER VIBRATORY AND VIBROIMPACT LOADING

The paper presents a comprehensive theoretical analysis of the dewatering processes of wet dispersed materials - including food production waste such as distillery stillage, brewery spent grain, sugar beet pulp, and coffee slurry - under vibratory and vibroimpact loading. The classification of moisture binding forms in colloidal capillary-porous bodies according to Rebinder is discussed in detail, distinguishing free moisture, capillary-bound (physico-mechanical), adsorption-bound (physico-chemical), and chemically-bound moisture fractions by binding energy. Free and physico-mechanically bound moisture accounts for over 65% of the liquid phase volume and is amenable to removal by mechanical methods. The rheological physico-mechanical characteristics of wet dispersed materials - elasticity, plasticity, viscosity, cohesion, adhesion, and inertial properties - are systematically reviewed. Models based on combinations of Hooke, Newton, and Saint-Venant bodies in series and parallel configurations are described, including the Shvedov-Bingham viscoplastic model, the Kelvin and Maxwell viscoelastic models, and the Bingham elastoviscoplastic model. A phenomenological mechano-rheological model for the full elastoviscoplastic-inertial behaviour of the material is presented. The theory of static pressing is analysed, including expressions for capillary pressure, neutral and effective pressure components, and liquid outflow velocity governed by Darcy's law. The fundamentals of vibratory loading are presented, with particular attention to conditions for transition into pseudofluidisation and vibroboiling states, effects of particle size and moisture content on required loading parameters, and the role of static punch pressure in suppressing lower-layer loosening. The governing equations of motion for dispersed systems under two-component harmonic vibration are formulated, and the energy balance method for linearising nonlinear damping is described. The study establishes the complete theoretical basis for systematic optimisation of vibratory and vibroimpact loading parameters to achieve maximum dewatering efficiency for food production waste materials.

Keywords: *wet dispersed materials, vibratory loading, vibroimpact dewatering, rheological models, Hooke body, Newton body, Saint-Venant body, capillary pressure, Darcy's law, pseudofluidisation, vibroboiling, food production waste, moisture content, phenomenological model, static pressing.*

Problem formulation. Dewatering of wet dispersed materials - including food production waste such as distillery stillage, brewery spent grain, sugar beet pulp, and coffee slurry - is one of the most energy-intensive and technologically critical processes in the food industry. Conventional mechanical dewatering equipment typically yields a final moisture content of 30-90%, necessitating subsequent thermal drying which drastically increases total energy consumption. Thermal drying of distillery stillage requires up to 2528 kWh/t on a drum dryer, while vacuum drying of beet pulp requires 740-760 kWh/t. The development of improved methods capable of achieving final moisture content in the range of 20-25% without thermal post-treatment therefore represents an important engineering objective with considerable economic significance.

The theoretical description of dewatering processes requires a rigorous rheological framework capable of representing the complex mechanical behaviour of wet dispersed materials under both static and dynamic loading. Such a framework must account for elastic, viscous, plastic, and inertial effects simultaneously. Its systematic development is an essential prerequisite for the rational design and optimisation of vibratory and vibroimpact dewatering equipment, and for identifying the fundamental physical mechanisms responsible for the superior performance of such equipment relative to conventional presses.

The fundamental scientific challenge consists in constructing tractable rheological models that, while sufficiently simplified for analytical and engineering use, adequately reflect the dominant physical mechanisms governing liquid expulsion from wet dispersed materials under various loading regimes. This challenge is compounded by the continuous evolution of material properties - porosity, filtration coefficient, particle contact geometry - during the pressing process itself, making purely static models inadequate for describing the dynamic conditions of vibroimpact treatment.

Analysis of recent research and publications. The theoretical foundations for investigating vibroimpact dewatering processes are provided by several intersecting bodies of prior work: rheological models of wet dispersed materials [1, 2], theories of static pressing [3, 4], studies of vibratory and vibroimpact processing [5, 6, 7], and the resonance-structural theory of vibroimpact inertial pressing of dry non-plastic powders [8, 9].

The deformation and flow behaviour of wet dispersed materials under mechanical loading is studied within the corresponding branch of rheology. As noted in the literature [1], constructing rheological models of real systems requires caution: models incorporating all material properties may become unacceptably complex for analysis, while models neglecting most properties may be physically incorrect. A practical compromise is offered by phenomenological mechano-rheological models that capture dominant elastic, viscous, plastic, and inertial effects through combinations of standard rheological bodies.

According to the classification of Academician Rebinder [10], the solid particles of the wet dispersed materials under consideration - food production waste - constitute colloidal capillary-porous bodies, since upon removal of liquid and compression they exhibit partial elasticity and partial fracture. This classification has fundamental implications for the selection of appropriate dewatering mechanisms, as different moisture fractions require qualitatively different approaches for their removal.

Prior experimental investigations of vibroimpact dewatering of food production waste [5, 6] demonstrated that the final moisture content following vibroimpact treatment does not exceed 20-25%, with processing throughput of 20-25 t/h and specific energy consumption of 2.7 kWh/t - a marked improvement over single-stage mechanical pressing. The theoretical explanation of these results requires a thorough understanding of the rheological behaviour and the mechanisms of liquid expulsion under combined static, vibratory, and impact loading.

Purpose of the study. The objective of the present work is to systematise and present the theoretical foundations for the analysis of dewatering processes of wet dispersed materials under vibratory and vibroimpact loading. Specifically, the study aims to: (1) classify the forms and binding energies of moisture in colloidal capillary-porous bodies; (2) describe the rheological physico-mechanical characteristics of wet dispersed materials and the phenomenological models used to represent them; (3) analyse the theoretical basis of static pressing, including capillary pressure, neutral and effective pressure components, and liquid filtration governed by Darcy's law; (4) present the governing equations of vibratory loading and determine the conditions for transition into pseudofluidisation and vibroboiling states; and (5) formulate the equations of motion of dispersed systems under two-component harmonic vibration.

Research results. According to Rebinder's classification, supplemented by Kazansky, all liquid contained in colloidal capillary-porous bodies may be divided, by binding energy E, into the following categories [10, 11]: free moisture; capillary-bound moisture (physico-mechanical bond); adsorption-bound moisture (physico-chemical bond); and chemically-bound moisture.

Chemically-bound moisture is retained most firmly, as its molecules form part of the solid phase and can only be removed by chemical interaction or calcination. Physico-chemical and osmotic interactions arise between liquid and solid particles in direct contact; the liquid molecules remain independent and isolated but are held near solid particle molecules, and may be separated by evaporation, desorption, or deadsorption [10]. Solid particles absorbing this moisture swell, but the volume of the swollen system W_{ns} is less than the sum of the volumes of the solid W_t and liquid W_r phases; the difference $DW = W_t + W_r - W_{ns}$ represents the contraction of the system.

Free moisture together with moisture having physico-mechanical bonds accounts for over 65% of the total liquid phase volume in the materials under consideration and is removed with sufficient efficiency by mechanical means [5, 7]. Adsorption-bound moisture within the hygroscopic range can sometimes be removed by mechanical methods, but this requires considerable expenditure of energy and time. Chemically-bound moisture cannot be removed mechanically at all. This hierarchical classification provides the fundamental basis for assessing the theoretical limits of mechanical dewatering efficiency.

The principal rheological physico-mechanical characteristics of wet dispersed materials relevant to mechanical dewatering processes include: elasticity, plasticity, and viscosity. In addition, cohesion, adhesion, and internal friction between particles must be taken into account [12]. Cohesion refers to intermolecular interactions between particles of the same phase; adhesion to analogous interactions between particles of different phases. In dynamic processes, including vibratory and vibroimpact treatment, the inertial properties of the processed material must also be considered.

In real wet dispersed materials under static or dynamic loading, the physico-mechanical characteristics described above are modelled by combinations of Hooke, Newton, and Saint-Venant bodies, representing elasticity, viscosity, and plasticity respectively (Figure 1). The most well-known models built from these simple elements include: the viscoplastic Shvedov-Bingham model, the viscoelastic Kelvin and Maxwell models, and the elastoviscoplastic Bingham model.

In real wet dispersed materials, during their static or dynamic loading, the above physical and mechanical characteristics are modeled using combinations of Hooke, Newton, and Saint-Venant bodies, which represent the elasticity, viscosity, and plasticity of the material, respectively [1] (Figure 1). The most famous models of complex structures built on the basis of these simple bodies/

Some complex models connect simple rheological bodies in series and parallel configurations (Figure 2). Simple rheological bodies connected in series sustain equal stress, and the total deformation equals the sum of deformations of each individual body. In parallel connection, the bodies sustain equal deformations, and the total stress is the sum of stresses sustained by each body [12].

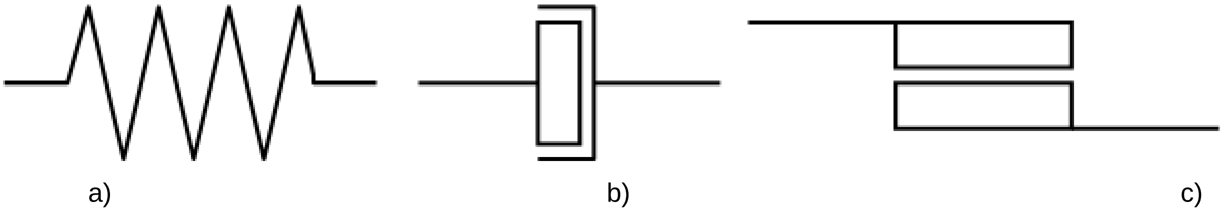

Fig. 1. Hooke's (a), Newton's (b) and Saint-Venant's (c) body models

The resultant stiffness for series and parallel connection is determined respectively as:

$$c_{\Sigma} = \frac{1}{\frac{1}{c_1} + \frac{1}{c_2} + \frac{1}{c_3}}; c_{\Sigma} = c_1 + c_2 + c_3. \quad (1)$$

In some of these complex models, simple rheological bodies can be connected to each other in series and in parallel (Figure 2) [13]. Simple rheological bodies without inertial elements connected in series act as links in a single chain and therefore must perceive the same stress, while the deformation of the entire sequence of rheological bodies will be equal to the sum of the deformations of each body. In parallel connection, simple rheological bodies without inertial elements perceive the same deformations, and the total stress perceived by their set is the sum of the stresses perceived by each individual body [13]. Thus, the resulting stiffness in series and parallel connection of elements (see Figure 2, a, b) is defined, respectively, as [13]

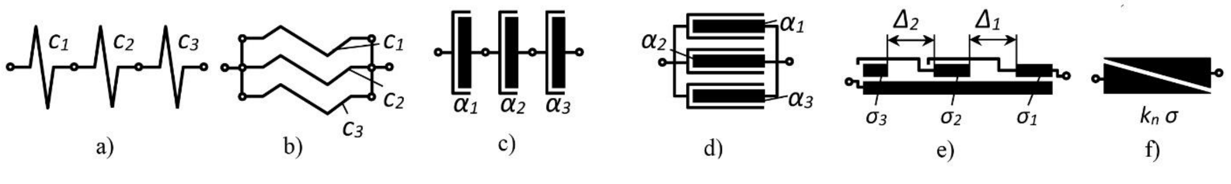

Fig. 2. Series and parallel connections of elastic (a, b), viscous (c, d) and plastic (e, f) elements

The materials under consideration constitute the most complex rheological systems - elastoviscoplastic-inertial - and may be described by phenomenological mechano-rheological models [3, 9], an example of which is shown in Figure 3. In this model, c_x, c_y denote stiffness coefficients along axes x and y; α_x, α_y - viscous damping coefficients; σ_x sigma_x, y - yield stress; m - mass of the material portion. Compaction along the x and y axes is modelled by wedge elements with transmission ratio i_x, y.

The moisture content U of the materials under consideration is defined as the ratio of the mass of the liquid phase m_r contained in a material portion to the total mass of the portion m_m:

$$U = \frac{m_p}{m_м} = \frac{m_p}{m_m} + m_p, \quad (2)$$

where m_t is the mass of the absolutely dry solid phase of the portion.

Methods for measuring the moisture content of the materials under consideration are described in detail in [12] and are classified into direct methods, in which the material is separated into solid and liquid phases, and indirect methods, which involve measuring physical quantities or properties functionally related to moisture content. Direct methods include the weight method, based on drying a sample of the material to a constant weight [12].

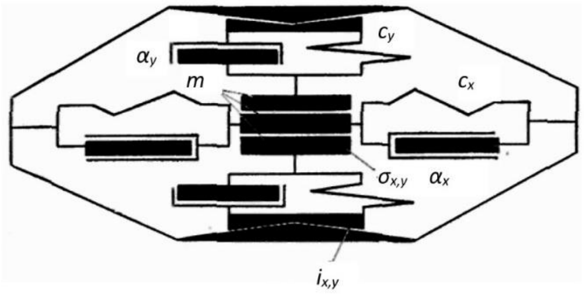

Fig. 3. Elastic-visco-plastic-inertial phenomenological model

Moisture content measurement methods are classified as direct methods, in which the material is separated into solid and liquid phases, and indirect methods, which involve measurement of physical quantities functionally related to moisture content. The gravimetric method, based on drying of a sample to constant mass, belongs to the direct methods and is widely used for food production waste materials.

Pressing is defined as the mechanical treatment of a material by compression under external forces. As a result of compressing a portion of wet dispersed material, the liquid phase is expelled with reduction in the volume and mass of the portion. The efficiency of the process is determined by the completeness of liquid phase removal, which in turn depends on the optimality of loading parameters and the technological capabilities of the equipment [3, 4].

In a material portion of volume W, three principal layers may be distinguished (Figure 4): a layer of solid particles with volume W_t and height H_t; a layer of the liquid phase (W_r, H_r); and a gas layer (W_g, H_g). Following placement of a punch on the material portion, the gas phase partly escapes and partly distributes within the liquid and solid layers; solid particles approach one another sufficiently closely for molecular cohesion forces to become active. Pressing can remove only that fraction of liquid which is bound to solid particles by mechanical and structural bonds. The greatest quantity of liquid is removed during the initial stage, after which the removal rate decreases and eventually ceases entirely.

In the general case, during pressing, it is necessary to create a pressure in the medium of the processed material that is greater than the capillary pressure p_σ of the free liquid of the portion, which can be determined by the formula [14]

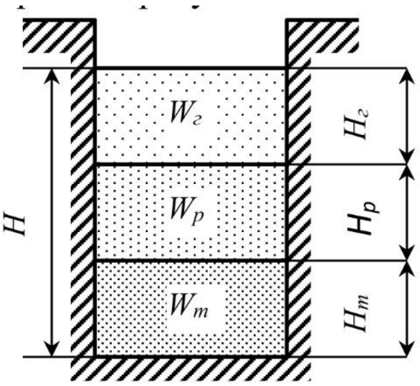

Fig. 4. Simplified structural diagram of a portion of wet dispersed material

During pressing it is necessary to create a pressure in the material exceeding the capillary pressure p_sigma of the free liquid, determined from the formula:

$$p_\sigma = \frac{2\cdot\sigma_{12}}{r}, \tag{3}$$

where σ_{12} is the surface tension coefficient between the gas and liquid phases; r is the capillary radius in and between solid particles. For a capillary with $r = 10^{-8}\ m$, $p_\sigma = 15\cdot 10^6$ Pa. In the hygroscopic range, the force F_k retaining liquid in the capillaries is determined from the relative air humidity corresponding to the equilibrium moisture content of the material:

$$F_к = \frac{R\cdot T_p}{M_м}\varphi_n, \tag{4}$$

The binding energy E_k of liquid with solid particles in the hygroscopic range is the moisture transfer potential and may be found from the corresponding expression (5).

$$E_к = -R\cdot T_p\cdot ln\varphi_n. \tag{5}$$

The maximum pressure p_m at the lower face of the punch is expressed as the sum of neutral pressure $p_{n.t}$ (dependent on the head loss of liquid flowing from the press mould) and effective pressure $p_{ef.t}$ (sustained by the solid particle skeleton):

$$p_м = p_{н.т} + p_{еф.т}. \tag{6}$$

The neutral pressure is determined by the resistance the liquid must overcome when flowing through channels between solid particles and through filter fabric holes in the press mould:

$$p_{н.т} = p_{н.ф} + p_{н.в} = \left(h_{н.ф} + h_{н.в}\right)g\cdot\rho_p, \tag{7}$$

where ρ_r is the liquid density. The velocity of liquid flow through the elementary cross-section of solid particles, under laminar conditions, is described by Darcy's law:

$$v_p = k_ф \cdot J\,\frac{1+\varepsilon_м}{\varepsilon_м}, \qquad (8)$$

where J is the hydraulic gradient; k_f is the filtration coefficient. Since liquid outflow occurs at atmospheric pressure, the simplified expression (9) follows, and the neutral pressure expression reduces to a function of porosity and filtration coefficient (10). The relationship between liquid outflow velocity and porosity is nonlinear; k_f varies continuously during pressing and depends also on temperature and moisture content of the material.

$$h_{н.ф} = h_p = \frac{v_p l_к \varepsilon_м}{k_ф\left(1+\varepsilon_м\right)}. \qquad (9)$$

$$p_{н.т} = \left(\frac{v_p l_к \varepsilon_м}{k_ф\left(1+\varepsilon_м\right)} + h_{н.в}\right) g \cdot \rho_p. \qquad (10)$$

The theoretical foundations of vibratory loading of wet dispersed materials in food industry processes were developed by Goncharevich and Uryev [5, 6]. They established that, to improve the efficiency of vibratory mechanical processing - increasing productivity and reducing specific energy consumption - it is necessary to increase the detachment velocities and accelerations of particles. As a result, the material may be transferred into a state of pseudofluidisation or vibroboiling.

Pseudofluidisation is defined as a reduction of deformation resistance with disruption of bonds between all particles, their non-detachment displacement, and a slight reduction in layer volume [13]. Vibroboiling involves reduction of rheological deformation resistance to a minimum, complete destruction of the initial structure, mutual displacement of particles with full detachment, achievement of maximum phase distribution uniformity, and an increase in layer volume.

According to Goncharevich [5], the principal advantages of vibratory loading are: firstly, the possibility of transmitting considerable energy to the material portion over a very short time interval with minimal particle displacement; secondly, the ability to regulate vibration frequency and amplitude over a wide range, enabling effective treatment of both large material volumes and layers of only a few micrometres in thickness.

Experimental investigations [7] established that vibratory loading causes solid particles with the greatest density and size to migrate to the upper layers. Furthermore, increasing the frequency or amplitude of vibratory loading increases the degree of solid particle compaction only up to a certain limit; beyond this, loosening of the material portion is observed. To prevent loosening when increasing pulse frequency, the amplitude must be correspondingly reduced, and vice versa [5].

Increasing solid particle size reduces the maximum achievable compaction degree, requiring increased actuator acceleration to maintain process efficiency. Similarly, increasing material moisture content requires higher particle acceleration to achieve maximum compaction. In most cases, acceleration up to the value of free-fall acceleration g does not produce adequate compaction, as the material merely enters a pseudofluidised state. Increasing acceleration beyond g leads to vibroboiling with loosening of lower layers, which may be prevented by applying static punch pressure to the material portion [5].

The process of vibratory compaction of solid particles proceeds non-uniformly over time, with decreasing productivity, explained by the increasing contact area between solid particles per unit volume of the portion [6]. With decreasing layer thickness of the processed material, the required particle accelerations may be reduced down to g without reducing the degree of compaction [5].

Damping in the dispersed systems under consideration is a complex phenomenon and may arise from: mutual dry or hydrodynamic friction of solid particles; resistance to their motion in the liquid or gas phases; flow of the phases through pores of the solid matrix; deformation of insufficiently elastic phases; and various cohesion forces. The presence of damping forces gives rise to nonlinear effects in the system subject to vibratory treatment, considerably complicating its investigation.

In liquid and gas highly dispersed systems, owing to the large active interfacial surface area, the free surface energy at the phase boundary increases, as does the role of molecular cohesion forces between particles, leading to formation of particle aggregates and spatial structures. In coarsely dispersed systems, where only friction forces act, spatial structures do not form, and mass transfer processes proceed at lower vibratory loading intensities [14].

Loading impulses transmitted through the material medium are attenuated as they travel from lower to upper layers; the degree of attenuation depends on the material properties, as well as the intensity and character of the vibrations [5]. Additionally, impulses are transmitted with a phase shift, the magnitude of which for finely dispersed materials with poor gas permeability may reach 180 degrees. A partial vacuum may develop between the actuator element of the vibratory equipment and the lower layer of finely dispersed material adjacent to it during loading.

In practice, the energy balance method is widely employed: energy dissipated per cycle due to real resistances is equated to energy losses from equivalent viscous resistances. This allows complex nonlinear damping to be reduced, with sufficient accuracy for engineering purposes, to viscous and elastic resistances. Thus, any multi-phase dispersed system may be modelled by standard elastoviscoplastic-inertial phenomenological models and methods of phenomenological rheology [5].

Damping of oscillations in the material medium may also occur at frequencies below the lower natural frequency of the medium, in which case exponential waves propagate through the medium with oscillation amplitude decreasing exponentially with distance from the vibration source [15]. Therefore, to achieve deeper vibratory processing, excitation frequencies must exceed the lower natural frequency of the medium. Accordingly, in determining energy consumption, a rheological model must account for the variability of oscillation amplitude and the possibility that part of the medium does not participate in oscillations at all.

The equations of motion of a dispersed system subjected to vibrations in the x-direction and y-direction are [5]:

$$q_y m_y \ddot{y} = -q_y m_y \ddot{y}' - c_y y - \alpha_y \dot{y} - \alpha_y' \left(\dot{y} + \dot{y}'\right) - \left(1 - q_x\right) m_x g - sign\left(\dot{y}\right) \mu_x \left(1 - q_x\right) m_x g;$$
$$q_x m_x \ddot{x} = -q_x m_x \ddot{x}' - c_x x - \alpha_x \dot{x} - \alpha_x' \left(\dot{x} + \dot{x}'\right) - \left(1 - q_x\right) m_x g - sign\left(\dot{x}\right) \mu_x \left(1 - q_y\right) m_y g, \quad (11)$$

where m_x, m_y are the total masses of the material portion; q_x, q_y are coefficients accounting for the fraction of total mass participating in oscillations; m_{ux} is the dry friction coefficient in the x-direction. The law of motion of a dispersed system under two-component harmonic vibration with amplitudes A_x, A_y, angular frequency omega, and phase shift gamma between the component motions may be expressed as [5]:

$$x' = A_x \sin \omega \cdot t; \dot{x}' = A_x \omega \cdot \cos \omega \cdot t;$$
$$y' = A_y \sin(\omega \cdot t + \gamma); \dot{y}' = A_y \omega \cdot \cos(\omega \cdot t + \gamma). \quad (12)$$

Substituting (12) into (11), performing linearisation and transformation of the resulting equations yields expressions for the optimal loading parameters of the material portion - in particular, conditions for transition into a vibroboiling state. These expressions form the theoretical basis for the engineering design of vibratory and vibroimpact dewatering equipment for food production waste materials.

Conclusions.

1. The classification of moisture binding forms in wet dispersed food production waste materials establishes that free and capillary-bound moisture accounts for over 65% of the total liquid phase volume and is removable by mechanical means, while adsorption-bound moisture requires elevated energy input and chemically-bound moisture is not mechanically removable. This hierarchy defines the theoretical upper limit of dewatering efficiency achievable by mechanical methods.

2. Wet dispersed materials constitute elastoviscoplastic-inertial rheological systems described by phenomenological models combining Hooke, Newton, and Saint-Venant bodies in series and parallel configurations. The resultant stiffness obeys standard composition rules, enabling systematic model construction for specific food production wastes including distillery stillage, brewery spent grain, sugar beet pulp, and coffee slurry.

3. The theory of static pressing establishes that effective liquid removal requires overcoming capillary pressure (up to 15 MPa for fine capillaries $r = 10^{-8}$ m), with the maximum pressing pressure comprising neutral and effective components. Liquid outflow velocity is governed by Darcy's law and is a nonlinear function of porosity; both the filtration coefficient and hydraulic gradient vary continuously during pressing and depend on temperature and moisture content.

4. Vibratory loading enables transfer of the material into pseudofluidisation or vibroboiling states, characterised by disruption of inter-particle bonds and intensive liquid expulsion. Transition to vibroboiling requires acceleration exceeding g for materials with high moisture content; simultaneous static punch pressure prevents lower layer loosening and is essential for achieving minimum final moisture content values of 20-25%.

5. The equations of motion for two-component harmonic vibratory loading, following linearisation via the energy balance method, yield expressions for optimal amplitude, frequency, and phase shift parameters. For finely dispersed materials with poor gas permeability, the phase shift of transmitted loading impulses may reach 180 degrees, which must be accounted for in the design of vibratory and vibroimpact dewatering equipment.

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ДОСЛІДЖЕННЯ ПРОЦЕСІВ ЗНЕВОДНЕННЯ ВОЛОГИХ ДИСПЕРСНИХ МАТЕРІАЛІВ ПРИ ВІБРАЦІЙНОМУ ТА ВІБРОУДАРНОМУ НАВАНТАЖЕННІ

У статті представлено комплексний теоретичний аналіз процесів зневоднення вологих дисперсних матеріалів, включаючи відходи харчового виробництва, такі як барда спиртового заводу, пивна дробина, жом цукрових буряків та кавова суспензія, під впливом вібраційного та віброударного навантаження. Детально обговорюється класифікація форм зв'язування вологи в колоїдних капілярно-пористих тілах за Ребіндером, з розрізненням вільної вологи, капілярно-зв'язаної (фізико-механічної), адсорбційно-зв'язаної (фізико-хімічної) та хімічно зв'язаної фракцій вологи за енергією зв'язку. Вільна та фізико-механічно зв'язана волога становить понад 65% об'єму рідкої фази та піддається видаленню механічними методами. Систематично розглянуто реологічні фізико-механічні характеристики вологих дисперсних матеріалів - еластичність, пластичність, в'язкість, когезія, адгезія та інерційні властивості. Описано моделі, засновані на комбінаціях тіл Гука, Ньютона та Сен-Венана в послідовній та паралельній конфігураціях, включаючи в'язкопластичну модель Шведова-Бінгема, в'язкопружні моделі Кельвіна та Максвелла, а також пружно-віскопластичну модель Бінгема. Представлено феноменологічну механореологічну модель для повної еласто-в'язкопластично-інерційної поведінки матеріалу. Проаналізовано теорію статичного пресування, включаючи вирази для капілярного тиску, нейтральної та ефективної складових тиску, а також швидкості витоку рідини, що визначається законом Дарсі. Представлено основи вібраційного навантаження, з особливою увагою до умов переходу в стани псевдофлюїдизації та віброкипіння, впливу розміру частинок та вмісту вологи на необхідні параметри навантаження, а також ролі статичного тиску штампування у придушенні розпушення нижнього шару. Сформульовано визначальні рівняння руху для дисперсних систем за умов двокомпонентної гармонічної коливання та описано метод енергетичного балансу для лінеаризації нелінійного демпфування. Дослідження встановлює повну теоретичну основу для систематичної оптимізації параметрів вібраційного та віброударного навантаження для досягнення максимальної ефективності зневоднення відходів харчового виробництва.

Ключові слова: *вологі дисперсні матеріали, вібраційне навантаження, віброударне зневоднення, реологічні моделі, статичне пресування, капілярний тиск, псевдозрідження, віброкипіння, відходи харчових виробництв, вологість..*

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Стаття надійшла 10.04.2026
Стаття прийнята 21.04.2026
Опубліковано 28.05.2026