1. Hryhorii KALETNIK[1], 2. Olena SOLONA[1], 3. Borys KOTOV[2], 4. Serhii STEPANENKO[3], 5. Viktor SHVYDIA[3], 6. Roman KALINICHENKO[4], 7. Ihor TVERDOKHLIB[1], 8. Yurii POLIEVODA[1]

Vinnytsia National Agrarian University (1), Podillia State University (2), Institute of Mechanics and Automatics of Agroindustrial Production (3), Nizhyn Agrotechnical Institute (4)
ORCID: 1. 0000-0002-4848-2796; 2. 0000-0002-4596-0449; 3. 0000-0001-6369-3025; 4. 0000-0002-8331-4632; 5. 0000-0002-8113-2173; 6. 0000-0001-9325-1551; 7. 0000-0003-1350-3232; 8. 0000-0002-2485-0611.

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The usage of the elemental base of the vibratory mill with the spatial circulation movement of material to create drying rig

***Abstract**. The analysis of existing vibration rigs revealed that the most promising is the use of vibro-milling chambers with spatial-circulation movement of dispersed material for thermal processing of grain, in particular drying. A mathematical description of the grain drying process and design parameters of the installation have been developed. Using these experimental data, the indicators of the vibrating dryer, that was created on the basis of the grinding chamber of the vibratory mill, were determined.*

Streszczenie.** Analiza istniejących urządzeń wibracyjnych wykazała, że najbardziej obiecujące jest zastosowanie komór wibromielących z przestrzenno-cyrkulacyjnym ruchem materiału rozproszonego do termicznej obróbki ziarna, w szczególności suszenia. Opracowano opis matematyczny procesu suszenia ziarna oraz parametry projektowe instalacji. Wykorzystując te dane doświadczalne wyznaczono wskaźniki suszarki wibracyjnej, która powstała na bazie komory mielenia młyna wibracyjnego.* (Wykorzystanie podstawy elementarnej młyna wibracyjnego z przestrzennym ruchem cyrkulacyjnym materiału do stworzenia suszarki***)

Keywords: drying, vibration rig, vacuum, conductive heating, grain.
Słowa kluczowe: suszenie, urządzenie wibracyjne, próżnia, ogrzewanie przewodzące, ziarno.

Introduction

One of the progressive directions of intensification of the processing of dispersed agricultural materials is the application of vibration technologies, which are widely used in various branches of the processing industry and, in particular continuous vibration machines with spatially-circulating movement of loading.

A special class of such machines are vibratory grinders of bulk materials – vibratory mills. The technological features of such machines are intensive low-energy mixing of the material in the chamber during its spatial circulation in direct or closed cycles. In practice, the material (load) under the action of the generated vibration field rotates in cylindrical chambers forming a loosened continuous rotating layer that is in close contact with the inner surface of the chamber. Such a mechanism of the process of moving and mixing bulk material is very attractive for organizing the processes of heat treatment or drying of wet dispersed materials by supplying thermal energy to the material and removing residual moisture from the vibrating chamber.

Thus, there is a real opportunity to use the created and tested element base, namely connected grinding chambers with spatial circulation of the load for heating or drying dispersed materials.

Given that the vibromechanical characteristics of the vibratory mill have been sufficiently studied and covered in publications [9, 11], there is a need for an analytical (as a first stage) study of the thermal processes that determine the modes of the thermal drying process of the material during circulation-spatial movement.

Analyzing the ways to solve the problem

Convective drying in a dense moving (mostly gravitational) layer remains the main method of grain drying in farms. The disadvantages of this method are the shielding of up to 30% of the heat transfer surface and significant heat losses with the spent drying agent [1]. Significant intensification of grain drying can be achieved by using vibration liquefaction of the grain layer [2-5]. Vibrational action on the grain material loosens the dense layer, increases the uniformity of grain processing by the drying agent, and eliminates local overheating of individual particles [4, 5]. In recent years, research in the field of drying in a vibrating bed has been directed in the areas of improving drying modes [6], using combined methods of energy supply to the material [7, 8], using infrared radiation [7], and conductive heat transfer of thermal energy to the material [12]. The analyzed studies [2-8, 12] mainly concern the intensification of convective heat and mass transfer, but significant energy losses with the spent drying agent do not allow full use of the energy supplied to the material.

At the same time, significant energy efficiency of grain dryers can be achieved by applying conductive heat supply directly to the material layer [12, 14, 15] and using the drying agent not as a heat carrier, but as a medium for absorbing and removing moisture. Good results were also achieved by vacuuming the drying chamber [16]. The processes of studying the processes of mixing and transporting material in a spatially circulating layer, for example, vibratory mills with various options for using vibration fields, are in sufficient detail in works [9, 10].

However, the processes of heat and mass transfer in devices with spatially circulating material movement under conductive heat supply remain poorly understood, although the effectiveness of this method of heat transfer has been confirmed in [13, 14].

Formation of the research objective

Construction of a mathematical model of the drying process to determine the modes of heating and dehydration of grain material during circulation in a vibrating chamber with a conductive energy supply and partial vacuuming of the chamber, to expand the technological capabilities of the «vibromill» type installations.

Materials and methods

As an installation for heating and drying grain material, we used a working body – the grinding chamber of Fig.1 of a vibratory mill [9, 10] additionally equipped with an electric heating element for supplying thermal energy to the material circulating in the chamber and a vacuum system for the volume of the material processing chamber. The chamber of Fig. 2 is made in the form of two cylindrical containers 1 and 2 mounted one from the other with consecutive open ends and connected by a connecting chute 3 in the rear part. The front ends of the cylindrical containers are interconnected by a reloading chute 4, which consists of a vertical chute 1 (Fig.1), which passes into an unloading tray 2 with an unloading valve 6 (Fig. 2). A heating element 9 (Fig. 2 b) in the form of a wound high-resistance wire 10 connected to a power source is fixed on the outer surface of the cylindrical walls 1, 2. A nozzle (7) is mounted at the end of the transition chute (3) to suck out water vapor released from the wet product in the chambers (1 and 2) using a compressor unit. To prevent the formation of a «stagnant zone» (a sedentary core of material [10]), a cylindrical perforated insert 11 connected to the nozzle 7 is installed in the center of the chamber, which is used as a «collector» of the steam-air mixture. To seal the chamber, sluice gates 12 and 13 are installed at the inlet 5 and outlet 6.

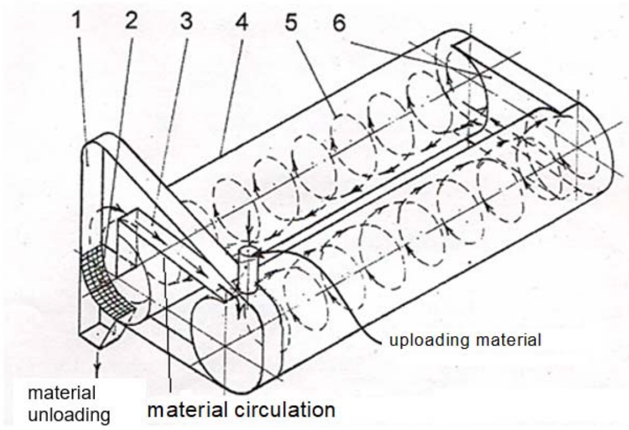

Fig. 1. Design and technological scheme of the grinding chamber of a vibratory mill

The thermal drying vibratory installation works as follows. After starting the drive – vibration exciter and applying voltage to the heating element, under the action of the formed flat vibration field created by the vibration exciter of the containers, vibrations are transmitted to them, as a result of which the material is transferred to the spatial circulation movement along the containers. The material acquires a rotational motion and, in contact with the heated surface of the containers, receives heat from it, which is used to heat the wet material and evaporate moisture, which is removed from the chamber in the form of a vapor-air mixture.

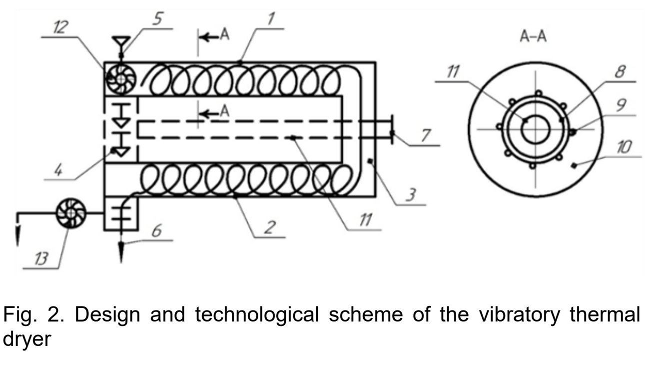

Fig. 2. Design and technological scheme of the vibratory thermal dryer

The drying-thermal vibratory plant can operate in two hydrodynamic modes: continuous transportation of material from inlet 1 to outlet 2 – the mode of ideal displacement – the plant operates continuously (Fig. 3); the second mode is periodic loading (batch plant) – the material circulates in a closed loop (1-2-3-1) – the mode of ideal mixing.

Let us consider the process of heat and mass transfer during the interaction of a vibration-liquefied rotating layer of grain material with a heated surface that performs oscillatory plane motion.

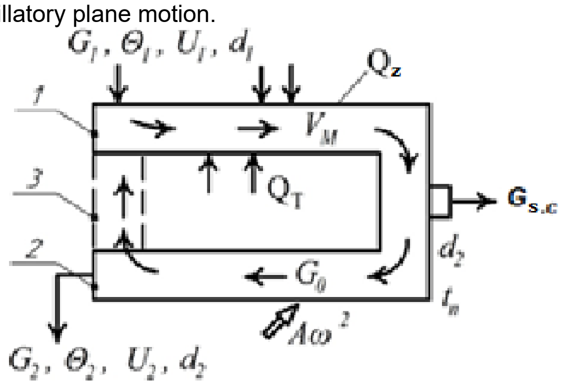

Fig. 3. Design scheme of the vibratory thermal dryer

As is known [17, 21-25], to intensify heat and mass transfer processes, such as grain drying with contact heat transfer, it is desirable that the processing material changes its position relative to the heated surface, i.e., that the conditions of heat and mass transfer of particles with the heating surface are constantly changing. This is achieved by the action of the vibration field on the elements (particles) of the grain material. To quantify the heat flux from a heated body to a heated particle, O. Krischer [17] proposed the following scheme: during the contact, the temperature on the surface of the contacting zones will be constant and equal to t_n, and the initial temperature t_z will remain on the back surface of the particle. In this case, the amount of heat received by the particle per unit time is determined by the expression:

(1) $$Q = F \cdot \frac{1}{\sqrt{\pi}}\sqrt{\lambda \cdot c \cdot \rho} \cdot \frac{1}{\sqrt{\tau_{\text{к}}}} \cdot (\theta_{\text{н}} - \theta_Z);$$

where F – the heat transfer surface, m^2; λ – the thermal conductivity coefficient, W/m·ºC; c – the specific heat capacity, J/kg °C; $\tau_{\text{к}}$ – the contact time, s; ρ – the density of the material, kg/m^3; $\theta_{\text{н}}$ – the temperature of the heating surface, ºC; θ_Z – the material temperature, ºC.

To determine the total amount of heat during the contact time *τ_k*, the product *Q·dτ* was integrated, as obtained in [17]:

(1') $$Q_\tau = F \cdot \frac{2}{\sqrt{\pi}}\sqrt{\lambda \cdot c \cdot \rho} \cdot \sqrt{\tau} \cdot (\theta_{\text{н}} - \theta_Z);$$

When calculating the heat transfer of a heating surface with a moving medium, the heat transfer coefficient α is usually used, and the amount of heat transferred per unit time is determined by Newton's equation:

(2) $$Q = \alpha F(\theta_{\text{н}} - \theta_{\text{M}});$$

where θ_{M} – the temperature of the moving heat carrier, ºC.

Considering that the vibrating grain liquefying layer is a moving heat-receiving medium, from comparing (1) and (2), the value of the contact heat transfer coefficient is obtained:

(3) $$\alpha = \frac{2 \cdot \sqrt{\lambda c \rho}}{\sqrt{\pi} \cdot \sqrt{\tau}};$$

where $\sqrt{\lambda c \rho}$ – coefficient of heat penetration, J/m^2 °C·$c^{1/2}$.

Differential equations for determining the non-stationary parameters of the drying process: temperature $\theta(\tau)$, moisture content $u(\tau)$ on the heating surface $\theta n(\tau)$ can be obtained from the equations of heat and material balances under the following assumptions:

- heat is transferred from the heating surface to the grain by contact heat conduction and the driving force is the temperature head (*θ_n-θ_M*);

- the heat transfer intensity is measured by the heat transfer coefficient α, which takes into account the heat transfer components (conductive, radiation);
- moisture is removed from the grain according to the law of evaporation from the free surface; we neglect the diffusion transfer from the material surface to the environment through the boundary layer of the vapor-gas mixture;
- the transfer potential is the difference in partial pressures at the material surface and in the medium, or the difference in water vapor concentrations at the material surface and in the surrounding vapor-gas medium.

The intensity of evaporation according to Dalton's law is determined by Eq:

(4) $$m_0 \frac{du}{\partial\tau} = W = F\frac{\beta}{R_{п}\cdot T}(p_s - p_{s.c.});$$

where m_0 – weight of absolutely dry material, kg; F – evaporation surface, m^2; β – mass transfer coefficient, mol /m^2·s; R_n – universal gas steel, R = 8,314 kg/s^2 mol·°C; T – steam temperature,°C; W – evaporation capacity of the surface, kg/s, p_s, $p_{s.c.}$ – is the partial pressure of vapor on the surface (at the surface temperature) and in the environment, Pa.

Since $\frac{p_s}{R_s\cdot T} = \rho_s$ – is the density (volume concentration) of the vapor, then equation (4) can be rewritten as:

(5) $$W = F\beta(\rho_s - \rho_{s.c.});$$

However, since density depends on temperature, it is easier to use the mass concentration – the moisture content of the vapor. Then the mass transfer equation in differential form can be written as follows:

(6) $$-m_0\frac{du}{\partial\tau} = F\beta(d_s - d_{s.c.});$$

where d_s, $d_{s.c.}$ – mass concentration of vapor on the surface and in the environment, kg/m^3. The mass transfer coefficient β is determined from the criterion equation [17]:

$\beta = Nu'\frac{D}{R_r}$, where Nu' – Nusselt's mass transfer criterion, mol/m^4; D – vapor diffusion coefficient, m^2/s; R_r – distance of steam movement (grain radius), m.

The diffusion coefficient of water vapor depends on the temperature and pressure of the vapor-gas mixture and is determined according to [17] by the formula:

(7) $$D = 0{,}112\frac{P_b}{P_c}\left(\frac{T}{273}\right)^{1{,}81}\frac{1}{3600};$$

where P_b, P_c – barometric pressure and pressure of the medium in the chamber, Pa.

Since the Nusselt mass transfer criterion is equal to $Nu' = 2$, during diffusion transfer of vapor, the mass transfer coefficient is determined by the formula:

(8) $$\beta = 2\cdot\frac{0{,}112}{3600}\frac{P_b}{P_c}\left(\frac{T}{273}\right)^{1{,}81}R_r^{-1};$$

Under the assumptions made, the mathematical description of the drying process in a vibratory dryer with circulatory-spatial movement of the material under vacuum conditions will be formed in the form of differential heat balance equations:

- for a drying chamber with a heater:

(9) $$m_{н}c_{н}\frac{d\theta_{н}}{d\tau} = P_{н} - \alpha F(\theta_{н} - \bar{\theta}_z) - kF_z(\theta_{н} - t_z);$$

- for the grain material in the chamber:

(10) $$m_z c_z\frac{d\theta_z}{d\tau} = G_z c_z(\theta_1 - \theta_z) + \alpha F(\theta_{н} - \bar{\theta}_z) - r\beta F\left[d_{н}(\theta_z) - \bar{d}_z\right];$$

- for a vapor-air mixture:

(11) $$m_{sc}c_{sc}\frac{dt}{d\tau} = G_{sc}c_{sc}(t_1 - t) - r\beta F\left[d_{н}(\theta_z) - \bar{d}_{c}\right];$$

- and material balance equations:

(12) $$m_{sc}\frac{dd}{d\tau} = G_{sc}(d_1 - d) + \beta F\left[d_{н}(\theta_z) - \bar{d}_{c}\right];$$

(13) $$-m_0\frac{du}{d\tau} = G_0(u_1 - u) + \beta F\left[d_{н}(\theta_z) - \bar{d}_{c}\right];$$

Equations (9)-(13) denote: $\theta_н$, θ_z, t – temperature of the heating surface, grain material and steam-air mixture, ºC; $P_{н}$ – power of the heating surface heater, W; α, β – heat and mass transfer coefficients, W/m^2·°C and kg/m^2·c; F, F_z – the grain heating surface and the outer surface of the drying chamber, m^2; c_z, c_{sc} – specific heat capacity of grain and steam-air mixture, J/kg °C; $c_{н}$ – specific heat capacity of the material of the heating surface with a heating element, J/kg °C; $m_{н}$, m_z, m_{sc}, m_0 – weight of the heater, grain material, steam-air mixture and dry air in the chamber volume, kg; G_z, G_0 – consumption (mass) of wet and absolutely dry grain, kg/c; G_{sc} – steam-air mixture consumption, kg/c; u_1, u – initial and current grain moisture content, kg/kg; d_1, d, $\bar{d}_c$ – Initial (inlet), current and average moisture content of the steam-air mixture, kg/kg; $d_{н}(\theta_z)$ – Is the moisture content of saturated steam on the grain surface at its temperature, kg/kg; t_1, θ_1 – temperature of the steam-air mixture and grain material at the inlet to the chamber, °C; t_z – ambient temperature, °C; k – is the heat transfer coefficient from the heater to the environment, W/m·ºC.

Research results

The obtained equations constitute a mathematical model (flow model of ideal mixing) of the non-stationary process of continuous drying of grain material and determine the change in time of the parameters of grain and the vapor-gas mixture at the outlet of the grain drying chamber.

To obtain analytical dependencies of the change in the parameters of grain material over time on the influencing factors, we simplify the system of equations (9-13). The dependence of the saturated moisture content of the vapor-air mixture is approximated by Eq:

(14) $$d''_s(\theta_z) = a\theta_z + b;$$

where a, b – linear approximation coefficients, $a = 3{,}4$; $b = -7{,}0$ g/kg.m.a.

With a preheated heating surface $\frac{d\theta_{н}}{d\tau} = 0$ its temperature is determined by the equation:

(15) $$\theta_s = A + B\theta_z;$$

where $A = \frac{P_{н} + kF_z t_z}{\alpha F + k_z F_z}$, $B = \frac{\alpha F}{\alpha F + k_z F_z}$.

The convective component of heat transfer is not taken into account, and the temperature of the vapor-air mixture at the outlet is assumed to be equal to the temperature of the grain material ($t = \theta_z$). Taking into account expressions (14) and (15), equations (10) and (12) take the form:

(16) $$T_1\frac{d\theta_z}{d\tau} + a_1\theta_z - b_1 = d;$$

(17) $$T_2\frac{dd}{d\tau} + a_2 d - b_2 = \theta_z;$$

where $T_1 = \frac{m_z c_z}{0{,}5r\beta F}$, $a_1 = \frac{\alpha F + r\beta Fa - \alpha Fb}{0{,}5r\beta F}$, $b_1 = \frac{G_z c_z\theta_1 + 0{,}5r\beta F d_1 - r\beta Fb}{0{,}5r\beta F}$, $T_2 = \frac{m_{sc}d}{\alpha\beta F}$, $a_2 = \frac{G_{sc} + 0{,}5\beta F}{\alpha\beta F}$, $b_2 = \frac{(G_{sc} - 0{,}5\beta F)d_1 + \beta Fb}{\alpha\beta F}$.

Reducing equations (16) and (17) to one, we have:

(18) $$A_1\frac{d^2\theta}{d\tau^2} + B_1\frac{d\theta}{d\tau} + C_1\theta = D_1;$$

(19) $$A_1\frac{d^2 d}{d\tau^2} + B_1\frac{dd}{d\tau} + C_1 d = D_2;$$

where $A_1 = T_1T_2$ i $B_1 = a_1T_2 + a_2T_1$, $C_1 = a_1a_2 - 1$, $D_1 = b_2 + b_1a_2$, $D_2 = b_1 + b_2a_1$.

Solution of inhomogeneous differential equations (18), (19) under initial conditions: $\tau = 0$, $\theta = \theta_0 = \theta_1$, $d = d_0 = d_1$, $\frac{d\theta}{d\tau} = \frac{dd}{d\tau} = 0$,

(20) $$\theta_z(\tau) = \frac{\theta_0 C_1 - D_1}{C_1(r_1 - r_2)}\left[r_1e^{r_2\tau} - r_2e^{r_1\tau}\right] + \frac{D_1}{C_1};$$

(21) $$d(\tau) = \frac{d_0 C_1 - D_2}{C_1(r_1 - r_2)}\left[r_1e^{r_2\tau} - r_2e^{r_1\tau}\right] + \frac{D_2}{C_1};$$

where $r_{1,2} = \frac{-B_1 \pm \sqrt{B_1^2 - 4A_1C_1}}{2A_1}$ – are the roots of the characteristic equation.

When using a vibratory dryer in a batch mode of operation (one-time loading of grain material weighin *m*) options $\theta_z(\tau)$ і $d(\tau)$ are determined by dependencies (20), (21) при $G_z = 0$.

The equation of drying kinetics (13) when using equations (14) and (20) takes the form:

(22) $$-\frac{m_0}{G_0}\frac{du}{d\tau} + u = u_1 + \frac{\beta F}{G_0}[a_1\theta(\tau) + C_1 - 0{,}5d_1 - 0{,}5d(\tau)];$$

Substituting the values of $\theta_z(\tau)$ and d(τ) into equation (22) after the transformations, we have:

(23) $$-\frac{m_0}{G_0}\frac{du}{d\tau} + u = \left[u_1 + \frac{D_z}{C_1}(D_1 - D_2)\right] + r_1 P e^{r_2\tau} - r_2 P e^{r_1\tau};$$

where $D_z = \frac{\beta F}{G_0}(C_1 - 0{,}5d_1)$, $P = D_z(aP_1 - 0{,}5P_2)$,

$$P_1 = \frac{\theta_0 C_1 - D_1}{C_1(r_1 - r_2)}, P_2 = \frac{d_0 C_1 - D_2}{C_1(r_1 - r_2)}.$$

Additionally, we'll mark:

$A_2 = \frac{G_0}{m_0}\left[u_1 + \frac{D_3}{C_1}(D_1 - D_2)\right]$, $B_2 = \frac{G_0 r_1 P}{m_0}$, $B_3 = \frac{G_0 r_2 P}{m_0}$ and rewrite the equation (23) in the form of:

(24) $$-\frac{du}{d\tau} + \frac{G_0}{m_0}u = A_2 + B_2 e^{r_2\tau} + B_3 e^{r_1\tau};$$

The solution of the inhomogeneous differential equation (24) is obtained as the sum of the solutions of the homogeneous and inhomogeneous equations:

$u_1(\tau) = C_0 e^{-A_3\tau}$, $u_2(\tau) = R_1 + R_2 e^{r_2\tau} + R_3 e^{r_1\tau}$,

in the form of:

(25) $$u(\tau) = C_0 e^{-A_3\tau} - A_2\frac{m_0}{G_0} + \frac{B_2}{r_2 - A_3}e^{r_1\tau} + \frac{B_3}{r_1 - A_3}e^{r_2\tau};$$

where $A_3 = \frac{G_0}{m_0}$, $u_2(\tau)$ was obtained by the method of indefinite multipliers. Sustainable integration C_0 determined from the initial conditions:

$\tau = 0$, $u = u_1$,

$$C_0 = u_1 - \frac{A_2}{A_3} + \frac{B_2}{r_2 - A_3} + \frac{B_3}{r_1 - A_3}.$$

Thus, the parameters of the grain drying process in a vibratory dryer under vacuum conditions: temperature $\theta(\tau)$ and moisture content u(τ) at the dryer outlet are determined from equations (20) and (25).

When calculating the parameters of the dryer according to the obtained equations (20) and (25), it is necessary to know the values of the heat transfer coefficients $\alpha_к$ and mass transfer β, and surfaces: $F_к$ – heat absorption and evaporation $F_з$ which can be determined from experimental data using batch drying models (according to O.V. Lykov):

(26) $$m_z c_z \frac{d\Theta}{d\tau} - m_o r\frac{du}{d\tau} = \alpha_k F_k(\theta - \theta);$$

and the Morel-modified version of Dalton's equation:

(27) $$m_0\frac{du}{d\tau} = \beta' F_{\text{B}}[d''(\theta) - d_c]\frac{P_B}{P_C};$$

where F_{B} – evaporation surface; $d''(\theta) = \alpha\theta - c$, kg/kg; d_c – moisture content of the vapor-air medium, kg/kg.

From equation (26) we have (replacing the derivatives with increments ($dx = \Delta x$) the formula for determining α_k:

(28) $$\alpha_k F_k = \frac{m_z c_z \Delta\theta + m_0 r\Delta u}{\tau_c LN};$$

where $LN = \frac{\theta_2 - \theta_1}{\ln\left(\frac{\theta_{\text{н}} - \theta_1}{\theta_{\text{н}} - \theta_2}\right)}$; $\Delta\theta = \theta_2 - \theta_1$, $\Delta u = u_1 - u_2$; θ_1, θ_2 і u_1, u_2 – initial and final values of material temperature and moisture content, °C і %; τ_c – drying time, s.

Since the heat from the heating surface is transferred to the grains not only by contact but also by radiation, the heat transfer surface F_k – the entire surface of the heater on which the grain is placed is taken.

The value of the mass transfer coefficient β' is determined from Eq. (27):

(29) $$\beta'^{F_{\text{B}}} = \frac{m_0\Delta u}{(a\theta - c - d_C)\tau_c};$$

The size of the evaporation surface can be determined (approximately) from the equation:

(30) $$F_{\text{B}} = \frac{\beta}{\beta'};$$

where β is the theoretical value according to the expression (8).

Fig. 4 shows the graphical dependences of changes in temperature and moisture content of grain over time determined experimentally when heating a monolayer of grain of mass m on a heating surface of area *F* at a stabilized surface temperature *θ_n*.

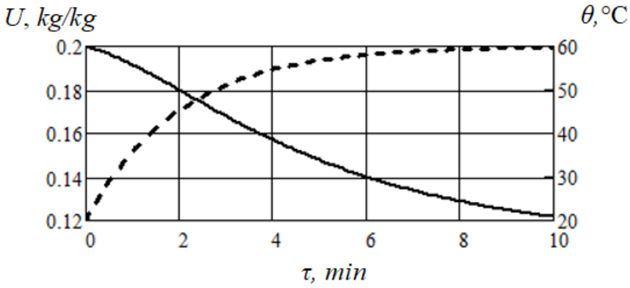

Fig. 4. Kinetics of grain drying and heating at atmospheric pressure

Fig. 5 shows similar dependencies for drying in a vacuum (*P*=20 kPa). From the graphs, we determine the average values (per process) of the drying rate $\frac{\Delta u}{d\tau}$ and heating $\frac{\Delta\theta}{d\tau}$ and calculate heat transfer coefficients $\alpha_{at} = 38{,}6\ \text{W/m}^2\text{К}$, $\alpha_{\text{вак}} = 78\ \text{W/m}^2\text{К}$, Rebinder's criterion $R\text{в}_{at} = 0{,}33$; $R\text{в}_{\text{вак}} = 0{,}23$. Thus, the defined vacuuming of the drying chamber allows for a significant intensification of the grain drying process.

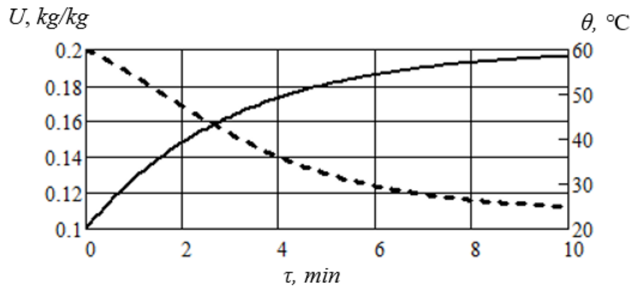

Fig. 5. Kinetics of grain drying and heating in a vacuum (*P* = 20 кPa)

According to the literature analysis, the heat transfer coefficient between the heating surface and the material in the vibrofluidized bed increases with increasing vibration parameters. Generalized, according to a number of researchers, the dependence of the heat transfer coefficient on the vibration parameters of the heating surface can be approximated by the equation:

(31) $$\alpha_{vib} = 86 + 6{,}7\frac{A\omega^2}{g};$$

where *A*, ω – amplitude and frequency of oscillations of the heating surface, mm s^{-1}; *g* – is the acceleration of gravity, m/s^2.

Using the Rebinder criterion$\left(Rb = \frac{c\,d\theta}{r\,du}\right)$ and the approximating equation of the graphical dependence Θ_τ (fig. 5):

(32) $$\Theta_\tau = 60{,}1 - 40{,}2\,e^{-0.51\,\tau};$$

from equation (24) we have:

(33) $$du = \frac{\alpha F(\theta_{\text{н}} - \theta_z)}{r \cdot m_z Rb}\,e^{-\frac{\alpha F}{m_z c_z}\tau}d\tau;$$

The graphical interpretation of the solution to equation (33) is shown in Fig. 6. As a theoretical curve of grain drying in a vacuum chamber that realizes vibration oscillations with a frequency of ω = 1.5·10^{-3} m [9].

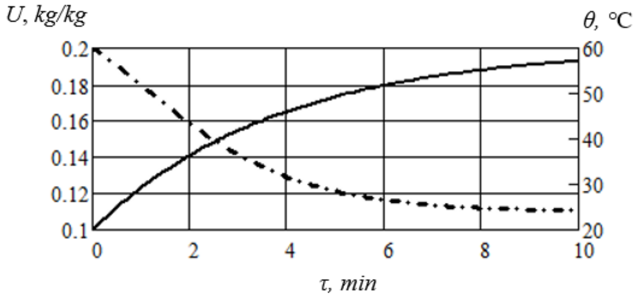

Fig. 6. Theoretical curves of grain drying and heating in a vacuum in the presence of vibration

As the graph shows *U(τ)* the drying exposure can be reduced to 223 s when using conductive heat supply in a vacuum drying chamber in the presence of heating surface vibration.

The mass transfer coefficient is determined according to the graph *U(τ)* by formula (27) is equal to β=7.3·10^{-6} m/s, by the formula (8) β=7.97·10^{-6} m/s. Thus, the theoretical dependence obtained corresponds to the assumptions made.

Having determined the unknown coefficients and constants contained in equations (20) and (25), we obtained graphical dependences of the transient process of grain drying in a vacuum vibrating chamber, i.e., the change in temperature over time $\theta_2(\tau)$ and moisture content $U_2(\tau)$ at the chamber exit in continuous mode – Fig. 7.

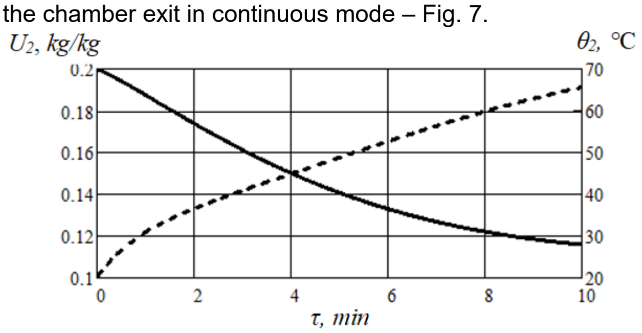

Fig. 7. Kinetic dependences of changes in material parameters at the chamber outlet $\theta_2(\tau)$, $U_2(\tau)$ from the time of drying

From the schedule $U_2(\tau)$ drying exposure is determined τ_c. From the empirical dependence of the material movement rate (ρ = 1400 kg/m^3) on the parameters of vibration impact *A* та ω: $V_з$= –27.67+0.16ω+11.25A+1461.6·10^{-3}+0.0157$A\omega$–3.44·10$^{-4}\omega^2$–3.11A^2–9.9ρ^2·10^{-8} the speed of movement is determined $V_з$ of the grain material. Knowing these parameters, the length of the chamber is calculated using an obvious ratio:

(34) $$L = \upsilon_z \tau_c;$$

where υ_z – speed of grain movement in the dryer, m/s.

Dryer performance depends on operating and design parameters:

(35) $$G_z = \upsilon_z S_{\text{н}} S'_z;$$

where S'_z – the cross-sectional area of the material in the chamber, m^2; $S_{\text{н}}$ – bulk density of the material, kg/m^3.

From relations (34) and (35) we have:

(36) $$G_z = \frac{L}{\tau_c} S_{\text{н}} S'_z = \frac{m_z}{\tau_c};$$

where m_z – weight of grain in the chamber, kg; L – length of the chamber, m.

Setting the dryer's performance G_z and determined τ_c from the graph (Fig. 7), through *u(τ)* calculate the weight of the material in the chamber m_z, its volume V_z and camera volume V_k:

(37) $$V_k = \varepsilon V_z = S'_k L;$$

where ε – camera fill factor; S'_k – cross-sectional area of the chamber $\left(S'_k = \frac{\pi D_k}{4}\right)$, m^2.

From the geometric relations, we determine the cross-sectional area of the camera:

(38) $$S'_k = \frac{\pi}{4}\sqrt{\frac{F_{\text{н}}}{\pi L}};$$

where $F_{\text{н}} = \pi D_k L$ – heating surface, m^2.

The energy characteristics of the dryer are determined by the energy (heat) balance equation:

(39) $$P_{\text{н}} = \alpha_k F_{\text{н}}(\theta_{\text{н}} - \bar{\theta}_z) = G_z c_z(\theta_2 - \theta_1) + G_0 r(u_1 - u_2) + kF_z(\theta_{\text{н}} - t_z);$$

Follows that:

(40) $$F_{\text{н}} = \frac{P_{\text{н}}}{\alpha_k(A,\omega)}(\theta_{\text{н}} - \bar{\theta}_z);$$

According to the data obtained on the kinetics of grain drying and heating *u(τ)*, *θ(τ)* and the calculated relations (29), (31)-(40), the parameters of the grain dryer were calculated. For the basic model of the grinding chamber of the vibratory mill MWE-5 [9], with an increase in the chamber volume to 14.5 dm3 and a heating element power of 7.5 kW, the grain drying capacity will be G_z = 157 kg/h. At the same time, the moisture tension of the chamber volume will be 25.2 kg/m^3, which is several times higher than for convective dryers.

Conclusions

1. The analysis of previous studies has established the high efficiency and prospects of heat treatment of grain materials in vibrating installations, in particular with spatial circulation of the processed material.
2. The formulated mathematical description of the process of drying grain material in a vibrating chamber with spatial-circular motion of the material under the conductive supply of thermal energy was used to determine the parameters of the drying plant in continuous and periodic modes.
3. Based on the data obtained by the calculations, it was found that with a drying chamber volume of 14.5 dm^3 and a supplied heating element power of 7.5 kW, it is possible to realize the process of drying grain with a capacity of 157 kg/h.

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Authors: KALETNIK Hryhorii – *Dr. Sc. in Economics, Professor, Academician NAAS of Ukraine, Head of the Department of Administrative Management and Alternative Fuel Resources, Vinnytsia National Agrarian University* (21008, 3, Sonyachna str., Vinnytsia, Ukraine); SOLONA Olena – *PhD in Engineering, Associate Professor, Faculty of Engineering and Technology, Vinnytsia National Agrarian University* (21008, 3, Sonyachna str., Vinnytsia, Ukraine, e-mail: solona_o_v@ukr.net); KOTOV Borys – *D. Eng. Sc., Professor, Faculty of Engineering and Technology, Podillia State University (32316, 12, Shevchenko Str., Kamianets-Podilskyi, Khmelnytskyi region, Ukraine), e-mail: eetsapk@pdatu.edu.u*; STEPANENKO Serhii – *D. Eng. Sc., Senior Researcher, National Scientific Center «Institute of Agricultural Mechanization and Electrification» (08631, 11,Vokzalna St, Glevakha, Fastiv district, Kiyv region, Ukraine), e-mail: stepanenko_s@ukr.net;* SHVYDIA Viktor – *PhD in Engineering, Associate Professor, Department of Mechanical and Technological Problems of Harvesting and Post-Harvest Processing of Grain and Oil Crops, Institute of Mechanics and Automatics of Agroindustrial Production* (08631, 11, Vokzalna str., Hlevakha, Ukraine), e-mail: Shvidia@gmail.com; KALINICHENKO Roman – *PhD in Engineering, Associate Professor, Department of Electric Power Engineering, Electrical Engineering and Electromechanics,* *Separated Subdivision NULESU, Nizhyn Agrotechnical Institute,* (16600, 10, Shevchenko str., Nizhyn, Ukraine), e-mail: rkalinichenko@ukr.net; TVERDOKHLIB Ihor – *PhD in Engineering, Associate Professor, Faculty of Engineering and Technology, Vinnytsia National Agrarian University* (21008, 3 Sonyachna str., Vinnytsia, Ukraine, e-mail: igor_tverdokhlib@yahoo.com); POLIEVODA Yurii – *PhD in Engineering, Associate Professor, Faculty of Engineering and Technology, Vinnytsia National Agrarian University* (21008, 3 Sonyachna str., Vinnytsia, Ukraine, e-mail: vinyura36@gmail.com).

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