SIMULATION OF HEAT EXCHANGE PROCESSES IN ROTARY SEED DRYER

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AGRICULTURAL MACHINES
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ABSTRACT

An important technological operation that ensures the formation of high-quality seed material is drying. This technological operation must have precise temperature modes of operation. It is also necessary to take into account the peculiarities of agricultural material. During post-harvest processing, the deviation from the set parameters leads to a decrease in the quality of raw materials. A set of studies is systematized to find ways to develop energy-saving drying methods. These studies were carried out by the Department of Agricultural Engineering named after Professor H. A. Hylis. Means that intensify the drying process are proposed. They are based on taking into account the properties of the seed material. This material is heat treated. The proposed design of a rotary dryer for loose agricultural seed materials with a spiral perforated surface of the drying chamber. Mathematical modeling of heat and mass transfer processes was performed to optimize the parameters of the drying unit. The seed material is dried on a spiral surface and mixed. The drying process will be represented by a sectional cascade type scheme with cross movement of the drying agent and seed material. The mathematical description of heat and mass transfer processes is presented by the microkinetic method. Its essence is the solution of the interaction model of flows of dispersed material and drying agent. The material is mixed within the sections. The kinetic regularities of a group of particles are characterized by the average value of temperature and humidity by volume. The results of the simulation, carried out in the form of a numerical experiment, are presented in graphic form.

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МОДЕЛЮВАННЯ ТЕПЛООБМІННИХ ПРОЦЕСІВ У РОТАЦІЙНІЙ СУШАРЦІ

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АНОТАЦІЯ

З-поміж важливих технологічних операцій, які забезпечують формування якісного насіннєвого матеріалу є сушіння. Ця технологічна операція потребує точного дотримання температурних режимів з урахуванням особливостей рослинного матеріалу. Відхилення від режимних параметрів спричиняє зниження якості рослинної сировини під час післязбирального оброблення. Систематизовано дослідження щодо пошуку шляхів формування енергозберігаючих методів сушіння, які виконані кафедрою аграрної інженерії імені професора Г. А. Хайліса ЛНТУ. Запропоновано засоби, які інтенсифікують процес сушіння і ґрунтуються на врахуванні властивостей насіннєвого матеріалу, що піддається сушінню. Запропонована конструкція ротаційної сушарки сипких сільськогосподарських насіннєвих матеріалів з спіралеподібною перфорованою поверхнею сушильної камери. З метою оптимізації параметрів сушильної камери виконано математичне моделювання тепломасообмінних процесів. Процес сушіння рослинного матеріалу на спіральній поверхні, що обертається, в рухомому шарі представлено схемою секційного каскадного типу з перехресним рухом сушильного агента та насіннєвого матеріалу. Математичний опис процесів тепло- та масопереносу виконано мікрокінетичним методом, сутність якого полягає в моделюванні взаємодії потоків перемішування дисперсного матеріалу в межах однієї секції та виведення сушильного агента. Кінетичні закономірності групи частинок рослинного матеріалу характеризуються середнім значення температури та вологості за об'ємом. Результати моделювання, проведеного у формі числового експерименту, представлені у графічній формі.

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INTRODUCTION AND PROBLEM STATEMENT

Drying is the most energy-intensive and responsible component of the post-harvest processing of crop products. Storing the harvest of various agricultural crops without control and reducing its moisture content to the standard value is impossible. At the same time, the grain drying process must occur in compliance with technological requirements and without loss of quality characteristics of the agricultural material. That is why the components of the economic effect from the production of crop products are, first of all, the use of energy-efficient methods, namely, the energy-saving approach to the formation of post-harvest processing and drying technology.

According to various studies in the field of theory and practice of drying, in particular the drying of capillary-porous colloidal bodies, which are agricultural materials, 50–60% of all energy costs are the costs of post-harvest processing of crop products and the process of drying them, including (*Podoliak, 1999; Dudarev, 2007; Panasyuk, 2008; Yashchuk, 2014; Kopets, 2016*). Therefore, research aimed at finding and justifying new methods of energy saving when drying agricultural materials are relevant and important tasks that would reduce the cost of the final product.

Today, when analyzing the kinetics of the drying process of capillary-porous colloidal bodies, two main approaches are distinguished: analytical and empirical studies (*Didukh, 2002*).

Analytical studies are based on the use of the theory of heat and mass transfer (*Bandura et al., 2018; Shvidia, 2022*). Based on this classical method, many mathematical models of the drying have been created (*Pakowski & Mujumdar, 1987*). However, this requires the installation of many thermophysical coefficients for various crops, simplification and reduction of the number of input parameters in the process of a numerical experiment, bringing the drying surface to a canonical form and many other assumptions that reduce the feasibility of using such models for agricultural production needs (*Gaivas, 2010*).

In turn, empirical studies of drying processes of agricultural plant materials require specialized equipment (*Elenkov, 1988*), time and additional costs, which is not always possible in real agricultural conditions. Such results are superficial and require clarification.

The Goal of the Study. Reducing energy costs for agricultural production is a prerequisite for the development of the crop production industry. The high cost of high-quality seed material is due to expensive post-harvest processing processes and can only be obtained with a balanced approach to the choice of drying modes and methods. This is especially important when forming seed material. Therefore, developing a clear scheme for implementing high-quality drying technology is an extremely important task. To implement and optimize such problems, it is advisable to construct mathematical models and conduct numerical experiments based on them. The implementation of such a modeling system for the design of a rotary seed dryer is the goal of this study.

MATERIALS AND METHODS

During the study, a review of information resources and literature sources was performed. The results obtained in 2010–2023 at Lutsk National Technical University on modeling the drying kinetics of agricultural plant materials were also taken into account. The research was carried out using methods of analysis, synthesis, scientific abstraction and an integrated approach. For a mathematical description of the drying process, approaches were used based on classical methods of modeling and physical and mathematical description, using the fundamentals of the theory of drying and heat-mass transfer.

RESULTS AND DISCUSSION

The Department of Agricultural Engineering of Lutsk National Technical University (LNTU) has completed a significant amount of work on the study of drying processes of various seed agricultural materials. The consequence of such research is the development of dryers that implement energy-saving drying modes, in particular, a rotary dryer for fine seed materials (*Zabrodotska, 2012*). The dryer contains a drying chamber, a diffuser, a fan and an electric heater (**Fig. 1**). The drying chamber is formed by a casing, which is fixed to the frame. In the upper part of the casing there is a perforated insert for draining the drying agent, and in the lower part there is a discharge window. At the end of the casing there is a hole for the loading auger of the drying chamber and one end comes out of the casing to the outside. A receiving hopper is

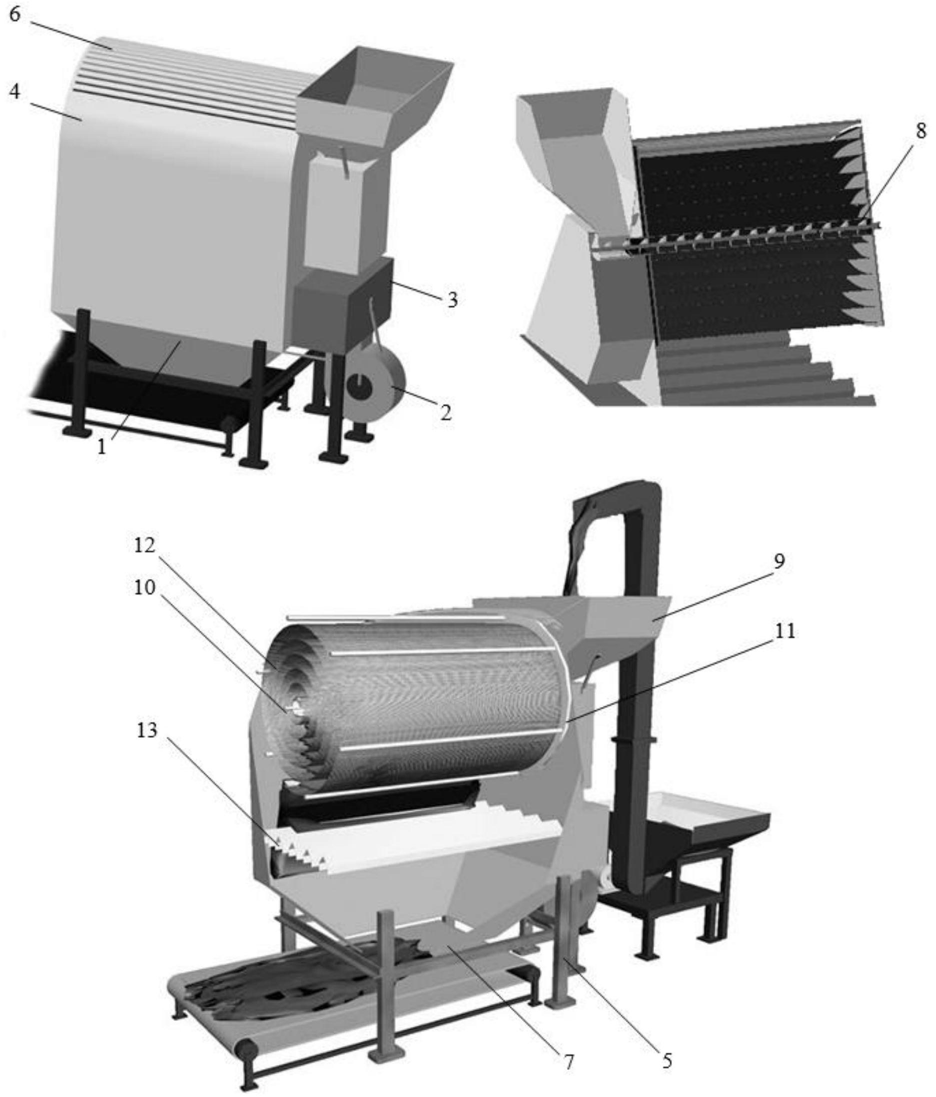

Fig. 1 – Rotary dryer:
1 – diffuser; 2 – fan; 3 – heater; 4 – casing; 5 – frame; 6 – perforated insert;
7 – unloading window; 8 – loading auger; 9 – receiving hopper; 10 – drive shaft; 11 – disk;
12 – spiral-shaped perforated surface; 13 – air boxes

attached to the auger. At the other end of the casing there is a hole for the drive shaft, on which a disk is fixed inside the casing. Attached to the disk is a perforated surface, a twisted spiral with a variable pitch, decreasing which from the center to the periphery ensures that the space to the horizontal axis of the drying chamber is filled with plant material.

Width perforated surface corresponds to the width of the drying chamber. The design of the latter includes seals that make it impossible for the drying agent to pass outside the material. Fan is connected through diffuser to the lower part of casing. Air boxes are located under the spiral surface.

The pouring material is loaded into the receiving hopper, then fed by a screw into the drying chamber onto a turn of the perforated spiral surface. As a result of the rotation of the drying chamber, the bulk material moves, sliding relative to the turns of the perforated surface from tier to tier. Having reached the outermost tier, the seed material, brought to the required moisture content, spills out between the boxes and is unloaded through the unloading window onto the conveyor.

According to the «counterflow» thermal scheme (**Fig. 2**), the temperature of the material increases in the direction of material unloading, and the temperature of the drying agent decreases in the direction from unloading to material supply.

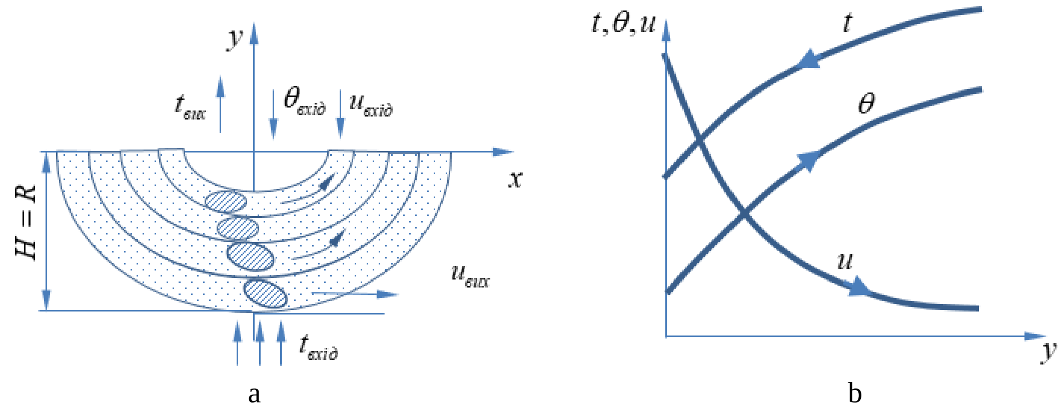

Fig. 2 – Generalized diagram of the processes of changing the parameters of the material (a) and coolant (b)

Let us represent the process of drying material on a rotating spiral surface in a moving layer with a diagram of a model of a multi-section (according to the number of spiral turns) cascade apparatus with cross-motion of the drying agent and material (**Fig. 2**). A mathematical description of the processes of heat and mass transfer is compiled using the microkinetic method, the essence of which is to solve the adopted model (scheme) of the interaction of flows of complete mixing of the solid phase (dispersed material within one section) and complete displacement of the gas phase (drying agent), as well as kinetic laws for a group of particles characterized by an average temperature and moisture content over the volume.

The general form of the relationship between the parameters that determine the intensity of drying depending on a number of external parameters of the process in the drying installation is established based on the analysis of the heat and material balance equations for the elementary layer and the entire volume of the material, as well as the equations for the kinetics of heat transfer from the drying agent to the material:

$$G_M C_M(\theta - \theta_1) = G_c C_c(t_1 - t) - rG_0(u_1 - u_2), \quad (1)$$

$$G_c(d_2 - d_1) = G_M(u_1 - u_2), \quad (2)$$

$$\alpha(t - \bar{\theta})\sigma \cdot S \cdot n \cdot \rho_M dh = -G_c C_c dt, \quad (3)$$

$$d = \frac{622}{10^{-5}} \varphi P''_H(t), \quad (4)$$

$$P''_H(t) = at + c, \quad (5)$$

where u – moisture content, kg/kg; t – material temperature, ºC; θ – temperature of the drying agent, ºC; r – specific heat of vapor formation, J/kg; α – heat transfer coefficient, W/(m^2·ºC); C – specific heat capacity, KJ/(kg·ºC); ρ_M – material density, kg/m^3.

Minimum consumption of fresh drying agent G_c and waste coolant temperature t_2 are determined from Equations (1) and (2), taking into account Equation (5):

$$0.622\varphi_2(at_2 + c) = $$
$$= d_1 + \frac{G_0(u_1 - u_2)C_p(t_1 - t_2)}{rG_0(u_1 - u_2) + G_M C_M(u)(\theta_2 - \theta_1)}, \quad (6)$$

$$G_c = d_1 + \frac{rG_0(u_1 - u_2) + G_M C_M(u)(\theta_2 - \theta_1)}{C_p(t_1 - t_2)}. \quad (7)$$

After substituting the numerical values of the initial parameters into equation (6) and (7) u_1, u_2, θ_1, θ_2, t_1, φ_2, d_1 and thermophysical properties of flows $C_M(u)$, C_p we get the required values G_c and t_2.

The number of turns of the spiral surface n is determined, and based on the given geometric parameters of the dryer, the initial data of each element of the conditional «cascade» is calculated:

- speed of the drying agent at the entrance to the drying chamber:

$$\upsilon_{вх} = P_i B G_C\ ; \quad (8)$$

- drying agent consumption for each cascade:

$$G_{ci} = P_i B \upsilon_{вх}\ ; \quad (9)$$

- filtration rate of the drying agent in the material layer:

$$\upsilon = \frac{\upsilon_{вх}}{\varepsilon}; \tag{10}$$

- the value of the Reynolds number is determined Re = $d_e\upsilon/\nu$, according to a criterion equation of the form: Nu = $A\cdot \mathrm{Re}^m(h_M/d_e)^p$, where Nu = $\alpha d_e/\lambda_e$, h_m – layer height;

- the heat exchange coefficient of the drying agent and material is determined (for fescue seeds: A = 0.72, m = 0.75, p = –0.9; for red clover: A = 2.7, m = 0.7, p = – 1.24);

- the mass of material in the «cascade» layer will be $m_i = V_i{\cdot}\rho_{Mi}$, where V_i – layer volume;

- the mass of completely dry substance is $m_{0i} = m_i/(1 + u_i)$;

- contact surface of the material with the drying agent (heat exchange surface): $F_i = m_i\sigma$, where σ – specific surface area of the material;

- the cooling coefficient of the drying agent is determined for each element of the «cascade»:

$$\eta_i = 1 - e^{-\frac{\alpha F_i}{G_c C_p}}. \tag{11}$$

According to certain indicators of final moisture content values u_k, material temperature θ_k (at the dryer outlet) and the temperature of the drying agent at the inlet t_1 initial conditions are determined.

Based on a simplified methodology, the initial conditions are determined by integral indicators, that is, the average volumetric parameters of an element of the material layer at each «cascade». The process diagram is shown in **Fig. 3**.

Initial conditions for the dryer (n = 4) are determined by sequentially solving the equation for each element starting from the last (initial):

$$\theta_{40} = t_1 - (t_1 - \theta_4)e^{-K_4L_4}, \quad K_4 = \frac{G_4\cdot C_p\cdot h_1}{m_1\cdot C'_{m_1}\cdot\delta_1}. \tag{12}$$

IV element:

$$t_2 = t_1 - R'_4(\theta_4 - \theta_{40}),\ R'_4 = \frac{G_0\cdot C'_{m_1}}{G_4\cdot C_p}, \tag{13}$$

$$U_{40} = U_4 + R''_4(t_1 - t_2),\ R''_4 = \frac{G_4\cdot C_p}{G_0(1+Rb_4(1+U_4)r_0}, \tag{14}$$

$$\theta_{30} = t_2 - (t_2 - \theta_4)e^{-K_3L_3},\ K_3 = \frac{G_3\cdot C_p\cdot h_3}{m_3\cdot C'_{m_3}\cdot\delta_3}. \tag{15}$$

III element:

$$t_3 = t_2 - R'_3(\theta_{40} - \theta_{30}),\ R'_3 = \frac{G_0\cdot C'_{m_3}}{G_3\cdot C_p}, \tag{16}$$

$$U_{30} = U_{40} + R''_3(t_2 - t_3),\ R''_3 = \frac{G_3\cdot C_p}{G_0(1 + Rb_3(1 + U_3)r_0}, \tag{17}$$

$$\theta_{20} = t_3 - (t_3 - \theta_3)\mathrm{e}^{-K_2L_2},\ K_2 = \frac{G_2\cdot C_p\cdot h_2}{m_2\cdot C'_{m_2}\cdot\delta_2}. \tag{18}$$

II element:

$$t_4 = t_3 - R'_2(\theta_{30} - \theta_{20}),\ R'_2 = \frac{G_0\cdot C'_{m_2}}{G_2\cdot C_p}, \tag{19}$$

$$U_{20} = U_{30} + R''_2(t_3 - t_4),\ R''_2 = \frac{G_2\cdot C_p}{G_0(1 + Rb_2(1+U_3)r_0}, \tag{20}$$

$$\theta_{вх} = \theta_{10} = t_4 - (t_4 - \theta_{20})e^{-K_1L_1},\ K_1 = \frac{G_1\cdot C_p\cdot h_1}{m_1\cdot C'_{m_1}\cdot\delta_1}. \tag{21}$$

I element:

$$t_{вх} = t_4 - R'_1(\theta_{30} - \theta_{10}),\ R'_1 = \frac{G_0\cdot C'_{m_1}}{G_1\cdot C_p}, \tag{22}$$

$$U_{вх} = U_{10} + U_{20} + R''_1(t_4 - t_{вих}),\ R''_1 = \frac{G_1\cdot C_p}{G_0(1+Rb_1(1+U_2)r_0}. \tag{23}$$

The speed of material movement on a rotating surface is determined $\upsilon_i = L_i/\tau_i$; where τ_i – time of one revolution.

The distribution of parameters of the material and drying agent in the direction of movement is determined by the following order.

Within the first zone in the direction of movement of the drying agent, the following calculation formulas will be valid (4 cascades in the direction of movement of the material):

$$\theta_4(y) = [\![t_1\text{-}(t]\!]_1 - \theta_{40})e^{-K_4y},\ K_4 = \frac{G_M\cdot C_p\cdot h_4}{m_4\cdot C'_{m_4}\cdot\delta_4}, \tag{24}$$

$$t_2(y) = \theta_4(y) + \big(t_1 - \theta_4(y)\big)e^{-K'_4L_4},\quad K'_4 = \frac{\alpha\cdot f_4}{G_4\cdot C_p\cdot h_4}, \tag{25}$$

$$U_y(y) = U_p + \big(U_{40} - U_p\big)\exp\left[-\frac{10^{-4}}{v_{My}}(0.367t_1\text{-}6)\right]y. \tag{26}$$

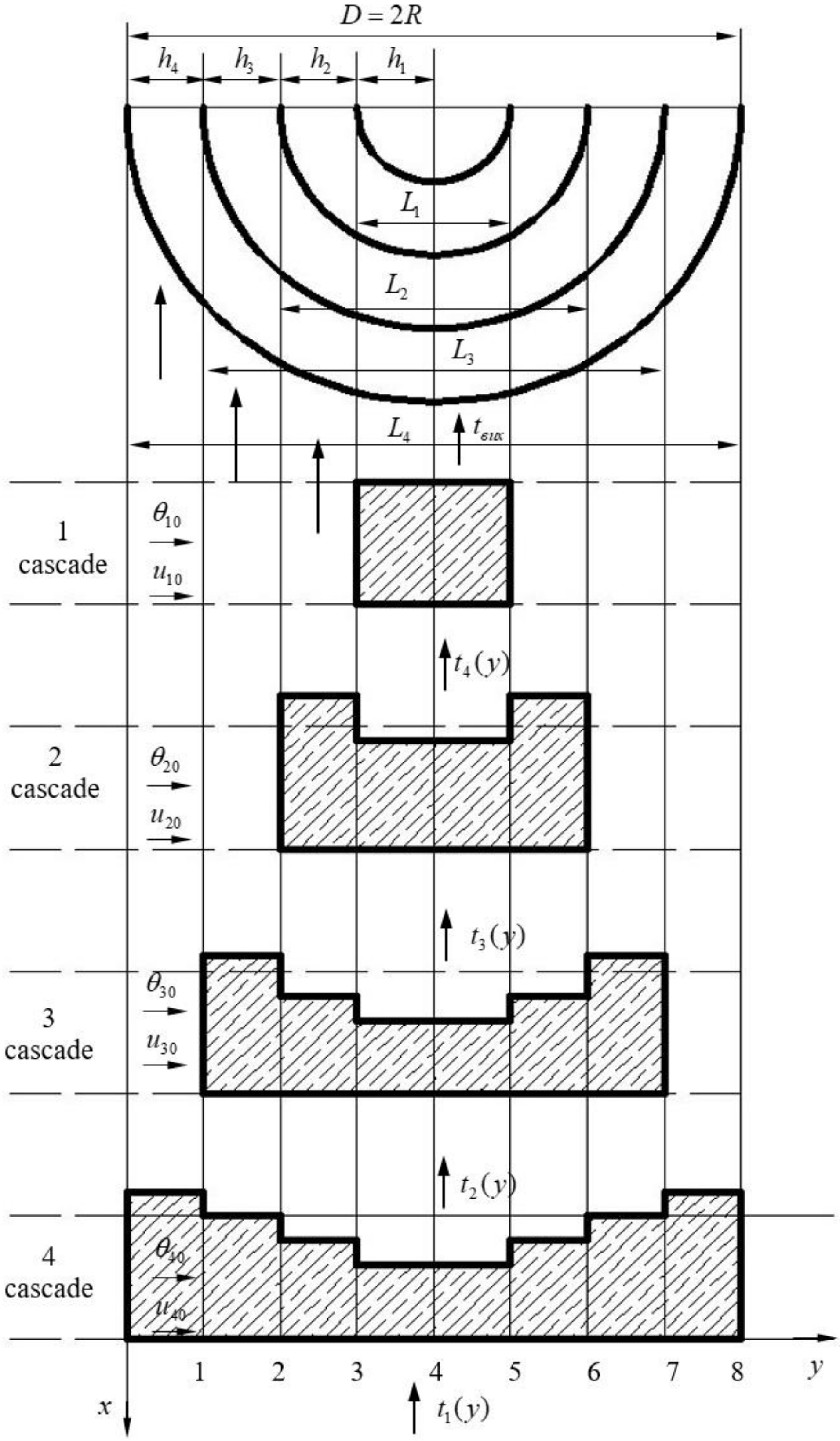

Fig. 3 – Calculation diagram of «cascade» drying at *n* = 4

For the second zone in the direction of movement of the drying agent (3 cascades):

$$\theta_3(y) = t_2'(y)+\left(t_2'(y)-\theta_{30}\right)e^{-K_3 y},\ y = O \dots L_3, \quad (27)$$

$$\theta_{40}' = t_1-(t_1-\theta_{40})e^{-K_4\left(\frac{L_4-L_3}{0.5}\right)}, \quad (28)$$

$$t_2'(y) = t_1-\left(t_1-\theta_{40}'\right)e^{-K_3' L_3}, \quad (29)$$

$$U_3(y) = U_p + \left(U_{30}-U_p\right)\exp\left[-\frac{10^{-4}}{v_3}(0.367t_3(y)-6)\right]y. \quad (30)$$

For the third zone (2 cascades):

$$\theta_2(y) = t_3'(y)+\left(t_3'(y)-\theta_{20}\right)e^{-K_2 y},\ y = O \dots L_2, \quad (31)$$

$$t_3'(y) = t_2'(y) - \left(t_2'(y)-\theta_{30}'\right)e^{-K_2' L_2}, \quad (32)$$

$$\theta_{30}' = t_2(y)-(t_2(y)-\theta_{30})e^{-K_3\left(\frac{L_3-L_2}{2}\right)}, \quad (33)$$

$$t_2(y) = \theta_2(y) + (t_3'(y)-\theta_2'(y))e^{-K_2' L_2}, \quad (34)$$

$$U_2(y) = U_p+\left(U_{20}-U_p\right)\exp\left[-\frac{10^{-4}}{v_2}(0.367t_2(y)-6)\right]y. \quad (35)$$

Numerical calculation (numerical modeling) of the parameters of a dryer with a spiral surface in four branches was performed under initial conditions:

$G_1 = 0.0589$ kg/s; $G_c = 2.4$ kg/s;
$U_1 = 0.33$; $t_1 = 55$ºC; $\tau_{одт} = 1500$ cm;
$G_2 = 0.046$ kg/s; $G_{cp} = 0.053$ kg/s; $U_к = 0{,}17$;
$\theta_1 = 15$ºC; $m = 80$ kg; $\underline{U_p} = 0.09$; $\theta \le 35$ºC;
$\overline{C}_M = 2$ KJ/(kg·ºC); $\overline{C}_P = 1.02$ KJ/(kg·ºC);
$r_0 = 2500$ KJ/kg; $W = 0.01297$ kg/s.

The simulation results are shown in the form of function graphs (**Fig. 4**) and (**Fig. 5**).

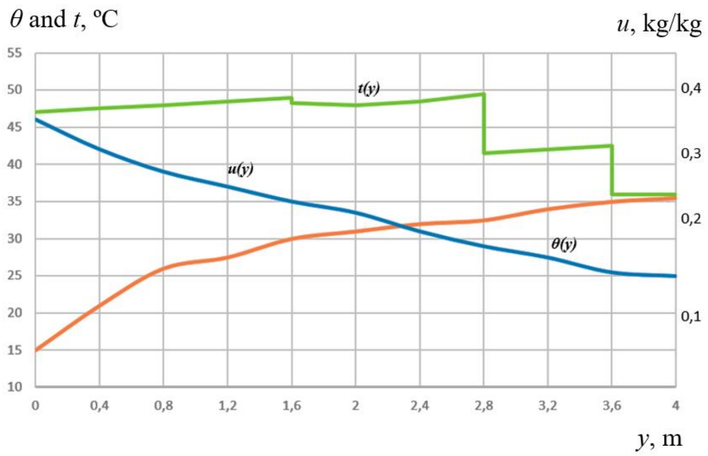

Fig. 4 – Results of the calculation of moisture content $u(y)$, seed temperature $\theta(y)$ and drying agent temperature $t(y)$

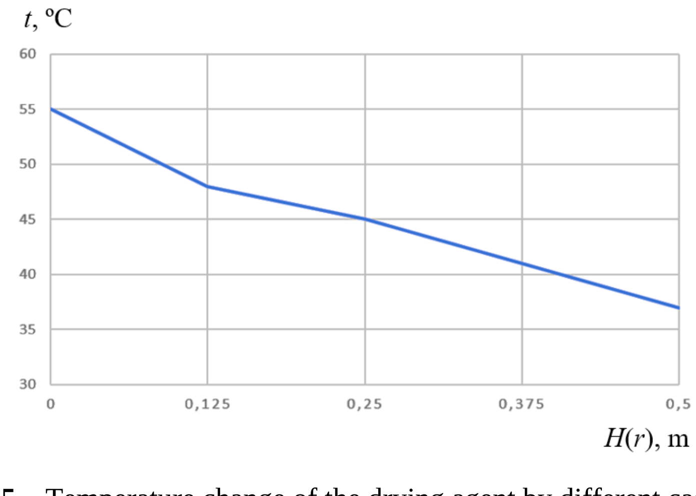

Fig. 5 – Temperature change of the drying agent by different cascades

CONCLUSIONS

Analysis of the research results indicates that to intensify the drying of agricultural seed materials, it is possible to use technical means that complement the drying process or implement the drying features of a specific seed material. The proposed design of the rotary dryer makes it possible to reduce the use of energy-saving drying methods, which is an urgent task today. In addition, such a dryer ensures high-quality implementation of the technological process of post-harvest processing of seed material.

The complex of theoretical and experimental studies carried out made it possible to describe the process of heat and mass transfer of bulk seed materials on the spiral surface of a rotary dryer. A mathematical model of the process of drying seed material has been obtained and a method for determining a number of thermophysical coefficients used in the process of numerical modeling has been developed. The modeling results indicate the feasibility of using the proposed methodology for generating numerical calculations for designing drying means and justifying the parameters of rotary dryers.

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