MATHEMATICAL DESCRIPTION OF THE PROCESS OF GRAIN DRYING BY THE CONVECTIVE METHOD

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Abstract. *The paper emphasizes that at present one of the tasks of the country's development is to increase grain production based on a significant increase in yield and reduce losses at all stages of its processing. During the period of harvesting and post-harvest processing, agro-climatic conditions are in most cases unfavorable, therefore, in the system of technological operations and post-harvest processing of seeds and grain, an important place belongs to their drying. In the article, the mathematical description of the grain drying process is based on a mathematical model in which the heat fluxes in the layer due to thermal conductivity were neglected, and shrinkage and pressure gradient were not taken into account. The zonal calculation method is considered, in which these characteristics are assumed to be constant.*

Keywords: *grain drying, bulk materials, moisture meter, grain, humidity.*

Grain is the most important product produced in agriculture. It is the basis for the production of a large number of different products, such as flour, cereals, feed, etc. One of the main aspects of grain processing is the process of its storage. The main task of this stage is to ensure the safety of grain crops in terms of minimizing their losses, improving quality characteristics at the lowest cost of labor and funds. The main characteristics during storage are the temperature of the grain mass, its humidity [1]

At present, one of the tasks of the country's development is to increase grain production on the basis of a significant increase in yields and reduce losses at all stages of its processing. During the period of harvesting and post-harvest processing, agro-climatic conditions are in most cases unfavorable, therefore, in the system of technological operations and post-harvest processing of seeds and grain, an important place belongs to their drying. As is known [2], grain moisture above 14% enhances the vital activity of microorganisms and increases its temperature, resulting in the risk of its spoilage. Unripened grain also contributes to this. Thus, the deterioration of the quality of rye, for example, can begin after 10 days if the humidity is 18% and the temperature is about 20 °C. At a humidity of 20% and a temperature of 20 ° C, 500 tons of grain loses, for example, 4 tons of its mass within 15 days. It follows from this that the grain must be processed immediately after harvesting to prevent its loss. Timely and properly carried out drying not only increases the stability of grain during storage, but also improves its food and seed qualities. Ensuring the high quality of drying requires the skillful use of grain drying equipment, its uninterrupted operation and the use of correctly selected drying modes. If the recommended drying modes are observed, the post-harvest ripening of grain is accelerated, the grain mass is leveled in terms of moisture and maturity, the color, appearance and other technological properties of the grain are improved. Drying has a depressing effect on the vital activity of microorganisms and pests. It has a positive effect on the yield and quality of products when processing grain into flour. that the grain must be processed immediately after harvesting to prevent its loss. Timely and properly carried out drying not only increases the stability of grain during storage, but also improves its food and seed qualities. Ensuring the high quality of drying requires the skillful use of grain drying equipment, its uninterrupted operation and the use of correctly selected drying modes. If the recommended drying modes are observed, the post-harvest ripening of grain is accelerated, the grain mass is leveled in terms of moisture and maturity, the color, appearance and other technological properties of the grain are improved. Drying has a depressing effect on the vital activity of microorganisms and pests. It has a positive effect on the yield and quality of products when processing grain into flour. that the grain must be processed immediately after harvesting to prevent its loss. Timely and properly carried out drying not only increases the stability of grain during storage, but also improves its food and seed qualities. Ensuring the high quality of drying requires the skillful use of grain drying equipment, its uninterrupted operation and the use of correctly selected drying modes. If the recommended drying modes are observed, the post-harvest ripening of grain is accelerated, the grain mass is leveled in terms of moisture and maturity, the color, appearance and other technological properties of the grain are improved. Drying has a depressing effect on the vital activity of microorganisms and pests. It has a positive effect on the yield and quality of products when processing grain into flour.

There are various ways to remove moisture from grain. Free moisture on the surface of the grain can be removed mechanically, for example, by spinning in a centrifuge or by mixing the grain with another substance that quickly absorbs water. Methods for drying grain can be conditionally divided into two groups. The first group includes the method of mechanical dehydration and the method of sorption drying. In both cases, moisture is removed from the grain in liquid form. The energy consumption for such drying is relatively small, and the moisture content of the grain can be reduced only by a small amount (1–2%). In addition, sorption drying of grain is long. The second group includes the thermal method of drying grain. The main amount of moisture in the grain is strongly associated with dry matter. It can be removed from the grain only by evaporation. With this method of drying, much more energy is required than with mechanical dehydration or sorption drying. Energy in this case is spent on overcoming the force of bonding moisture with the dry matter of the grain, as well as on the heat of vaporization. Such drying is called thermal. At grain-receiving enterprises, when preparing grain for storage, only thermal drying is used as the most effective one, which allows you to quickly reduce grain moisture.

The heat required to convert moisture into steam can be supplied to the grain in various ways: convective, conductive, infrared rays, and other methods. In grain drying, the most common method is the convective method, in which heat energy is transferred to the grain from heated gas (heated air or a mixture of air with fuel combustion products). An enlarged scheme of the technological process that implements this method is shown in fig. 1. The air-heated dryer consists of 3 zones: heating zone, drying zone and cooling zone. In the heating zone, by burning fuel or supplying thermal energy in some form (eg hot water), the air flow is heated and reaches a certain humidity and temperature. The heated air flow in the drying zone meets the grain flow. Heat and moisture exchange between air and grain takes place here. The air cools and heats the grain. At the same time, heat is required for vaporization. The humidity of the grain decreases, the released moisture passes into the air, while its absolute humidity increases. The grain leaves the drying zone relatively warm and requires cooling. This is carried out in the cooling zone by the flow of atmospheric air. The flow of grain leaves the cooling zone with a moisture content that is lower than its moisture content after the drying zone. Therefore, an additional drying effect is observed in the cooling zone. The cooling air absorbs moisture and leaves the cooling zone. In practice, 3 technically possible options for drying with heated air have found distribution: The released moisture passes into the air, while its absolute humidity rises. The grain leaves the drying zone relatively warm and requires cooling. This is carried out in the cooling zone by the flow of atmospheric air. The flow of grain leaves the cooling zone with a moisture content that is lower than its moisture content after the drying zone. Therefore, an additional drying effect is observed in the cooling zone. The cooling air absorbs moisture and leaves the cooling zone. In practice, 3 technically possible options for drying with heated air have found distribution: The released moisture passes into the air, while its absolute humidity rises. The grain leaves the drying zone relatively warm and requires cooling. This is carried out in the cooling zone by the flow of atmospheric air. The flow of grain leaves the cooling zone with a moisture content that is lower than its moisture content after the drying zone. Therefore, an additional drying effect is observed in the cooling zone. The cooling air absorbs moisture and leaves the cooling zone. In practice, 3 technically possible options for drying with heated air have found distribution: than its moisture content after the drying zone. Therefore, an additional drying effect is observed in the cooling zone. The cooling air absorbs moisture and leaves the cooling zone. In practice, 3 technically possible options for drying with heated air have found distribution: than its moisture content after the drying zone. Therefore, an additional drying effect is observed in the cooling zone. The cooling air absorbs moisture and leaves the cooling zone. In practice, 3 technically possible options for drying with heated air have found distribution: direct-flow drying; countercurrent drying; drying with cross movement of heated air.

The method of using cross-flow air (as well as cross-flow air) is the most unfavorable for drying. For almost the entire length of the dryer, the grain on the side where the air is supplied is drier than on the side where it exits. Despite this, almost all shaft dryers for grain operate on this principle. Good mixing of grain during passage through the dryer also contributes to improved drying.

The advantage of this method is the supply of air in any amount to a wide variety of zones with relatively small pressure losses, since the layer thickness remains constant, and the area of the incoming air flow also increases with an increase in the height of the dryer. Due to the possibility of supplying air to different zones, it is also possible to supply air at different temperature levels.

In [3-7], the mathematical description of the grain drying process is based on a mathematical model in which the heat fluxes in the layer due to thermal conductivity were neglected, and shrinkage and pressure gradient were not taken into account. We consider the zonal calculation method in which these characteristics are taken constant. In this case, the system of equations of A.V. Lykov is represented by equations in a spherical coordinate system:$r$is the spatial coordinate referred to the equivalent radius of the ball$r = x/R_{экв}$;$T = (\theta - \theta_0)/(\theta_c - \theta_0)$is the dimensionless temperature of the body, referred to the temperature of the mediumθ_c; $U = u/u_0$- dimensionless moisture content of the body, referred to the initial moisture contentu_0:

$$\frac{\partial T}{\partial \tau} = A_{11}\left(\frac{\partial^2 T}{\partial r^2} + \frac{2}{r}\frac{\partial T}{\partial r}\right) + A_{12}\left(\frac{\partial^2 U}{\partial r^2} + \frac{2}{r}\frac{\partial U}{\partial r}\right),$$
$$\frac{\partial U}{\partial \tau} = A_{21}\left(\frac{\partial^2 T}{\partial r^2} + \frac{2}{r}\frac{\partial T}{\partial r}\right) + A_{22}\left(\frac{\partial^2 U}{\partial r^2} + \frac{2}{r}\frac{\partial U}{\partial r}\right), \quad (1)$$

where $(U, T) \geq 0$, $(U,T) < \infty$ при $r \to 0$ $r \in [0,1]$, $\tau \in [0,1]$, $\tau = t / t_k$, with the condition that the solution is bounded:

$$|T, U| < \infty, \quad (2)$$

boundary conditions of the third kind:

$$-\left.\frac{\partial T(r,\tau)}{\partial r}\right|_{r=1} + a_1[1 - T(r,\tau)|_{r=1}] - a_2[U(r,\tau)|_{r=1} - u_p / u_0] = 0,$$
$$\left.\frac{\partial U(r,\tau)}{\partial r}\right|_{r=1} + b_1[1 - T(r,\tau)|_{r=1}] + b_2[U(r,\tau)|_{r=1} - u_p / u_0] = 0, \quad (3)$$

and initial conditions:

$$T(r,0) = 0, \quad U(r,0) = 1, \quad (4)$$

where the complexes of criteria are determined by the equations: $A_{11} = 1 + \varepsilon\, KoLu\, Pn$, $A_{12} = \varepsilon KoLu$, $A_{21} = LuPn$, $A_{22} = Lu$, $a_1 = Bi_q$, $a_2 = (1-\varepsilon)KoLuBi_m$, $b_1 = Pn\, Bi_q$, $b_2 = Bi_m(1-(1-\varepsilon)PnKoLu)$, and the criteria used are: $Ko = r_0 u_0 / c_q(\theta_c - \theta_0)$ – Kosovicha; $Lu = a_m / a$ – Likova; $Pn = \delta(\theta_c - \theta_0)/u_0$ – Posnova; $Fo = at / R^2_{экв}$ – Fure; the Fourier number; heat transfer and mass transfer Biot criteria, respectively $Bi_q = \alpha R_{экв} / \lambda$, $Bi_m = \beta R_{экв} / a_m$, где θ – Body temperature, θ_0 – initial body temperature, θ_c – medium temperature, K; u – moisture content of the examined body, u_p, u_0 – respectively, the equilibrium and initial moisture content of the body under study, (kg wl. / kg w. w.); ε – phase transformation criterion, dimensionless value characterizing the fraction of moisture moving in the form of steam; r_0 – specific heat of vaporization, kJ/kg; a_m – moisture diffusion coefficient, m^2/s; δ – thermogradient coefficient, 1/K; α – heat transfer coefficient, $W/(m^2 \cdot K)$; β – mass transfer coefficient, m/s, c_m – specific heat capacity of grain, J/(kg.K); ρ_0 – density of absolutely dry product, kg/m^3.

After replacing unknown functions:

$$T = Z(\tau, r) / r, \quad U = W(\tau, r) / r, \quad (Z, W) \in C^{(3)}(0 \leq r \leq 1), \quad (5)$$

system (1) relatively Z и W takes on a simpler form.:

$$\frac{\partial Z}{\partial \tau} = A_{11}\frac{\partial^2 Z}{\partial r^2} + A_{12}\frac{\partial^2 W}{\partial r^2}, \quad \frac{\partial W}{\partial \tau} = A_{21}\frac{\partial^2 W}{\partial r^2} + A_{22}\frac{\partial^2 W}{\partial r^2}, \quad (6)$$

with boundary conditions:

$$-\left.\frac{\partial Z(r,\tau)}{\partial r}\right|_{r=1} + a_1[1 - Z(r,t)]_{r=1} - a_2\left[W(r,t)|_{r=1} - u_p / u_0\right] = 0,$$
$$\left.\frac{\partial W(r,\tau)}{\partial r}\right|_{r=1} + b_1[1 - Z(r,t)]_{r=1} + b_2\left[W(r,t)|_{r=1} + u_p / u_0\right] = 0, \quad (7)$$

and initial conditions:

$$Z(0, r) = 0, \quad W(0, r) = r. \quad (8)$$

Since the functions T and U at $r \to 0$ limited by condition (2), which also agrees with the physical meaning of the problem, then from (5) it follows:

$$Z(\tau,r)\big|_{r=0} = W(\tau,r)\big|_{r=0} = 0 . \quad (9)$$

Thus, the problem is reduced to finding a solution to system (6) that satisfies boundary conditions (7), (9) and initial conditions (8). The complexity of this initial-boundary value problem lies not only in system (1), but also in the setting of boundary conditions of various kinds at $r=1$ conditions of mixed type (3), with $r=0$ Dirichlet conditions (9). If a solution were found, then on the spherical grain boundary at $r=1$ functions Z and W take on some values:

$$Z\big|_{r=1} = \varphi(\tau),\ W\big|_{r=1} = \psi(\tau) , \quad (10)$$

and $\varphi(\tau),\ \psi(\tau)$ – yet unknown functions.

The method used below to expand unknown functions into modified Fourier series allows us to replace the complex form of boundary conditions (7) with simpler and more convenient conditions (10). This leads to a simplification of the boundary conditions, but at the same time, two new unknown functions appear $\varphi(\tau), \psi(\tau)$, which will later be found under the boundary conditions (7). The following new problem arises: to find a solution to system (6) with initial condition (8) and boundary conditions (9) and (10), where the unknown functions $\varphi(\tau),\ \psi(\tau)$ should be determined so that the boundary conditions (7) are satisfied.

With this formulation, the solution of the problem can be represented by the following modified

Fourier series developed by Professor A. D. Chernyshov:

$$Z = M_z + \sum_{m=1}^{\infty} Z_m(\tau)\sin(m\pi r),\quad W = M_w + \sum_{m=1}^{\infty} W_m(\tau)\sin(m\pi r). \quad (11)$$

where dependencies M_z and M_w look like:

$$M_z = \varphi(\tau)r + \varphi_0(\tau)\left(\frac{r^2}{2} - \frac{r^3}{6} - \frac{r}{3}\right) + \varphi_1(\tau)\left(\frac{r^3}{6} - \frac{r}{6}\right),$$

$$M_w = \psi(\tau)r + \psi_0(\tau)\left(\frac{r^2}{2} - \frac{r^3}{6} - \frac{r}{3}\right) + \psi_1(\tau)\left(\frac{r^3}{6} - \frac{r}{6}\right). \quad (12)$$

Construction of boundary functions M_z and M_w is arranged so that expansions (11) converge uniformly inside the segment $r \in [0,1]$, and on its boundaries, together with the second partial derivatives with respect to the radius r up to and including the second order. Expressions for Z and W at (11) together with the second partial derivatives at $r=0$ and $r=1$ turn into identities. This property makes it possible to differentiate expansions (11) term-by-term twice and substitute them into differential equations (6), initial conditions (8), and boundary conditions (7). Thus, expansion (11) with expressions for M_z and M_w represent modified Fourier series. Their convergence has the order $(\pi m)^{-5}$, where m - ordinal number of the term in the sums of system (11). When functions (11) are substituted into (6) with $r=0$ and $r=1$ we get the equations:

at $r=0$: $A_{1,1}\varphi_0(\tau) + A_{1,2}\psi_0(\tau) = 0$, $A_{2,1}\varphi_0(\tau) + A_{2,2}\psi_0(\tau) = 0$, (13)

at $r=1$: $\varphi'(\tau) = A_{1,1}\varphi_1(\tau) + A_{1,2}\psi_1(\tau)$, $\psi'(\tau) = A_{2,1}\varphi_1(\tau) + A_{2,2}\psi_1(\tau)$. (14)

Therefore, from (13) and (14) we can find:

$$\varphi_0(\tau) = \psi_0(\tau) = 0 , \quad (15)$$

$$\varphi_1(\tau) = \frac{A_{2,2}\varphi'(\tau) - A_{1,1}\psi'(\tau)}{\Delta} ,\ \psi_1(\tau) = \frac{A_{1,1}\psi'(\tau) - A_{2,1}\varphi'(\tau)}{\Delta} , \quad (16)$$

where $\Delta = A_{11}A_{22} - A_{12}A_{21} \neq 0$ according to the task. Taking into account (15), expressions (11) take the form::

$$Z(r,\tau) = \varphi(\tau)r + \varphi_1(\tau)\left(\frac{r^3}{6} - \frac{r}{6}\right) + \sum_{m=1}^{\infty} Z_m(\tau)\sin(m\pi r) = 0,$$
$$W(r,\tau) = \psi(\tau)r + \psi_1(\tau)\left(\frac{r^3}{6} - \frac{r}{6}\right) + \sum_{m=1}^{\infty} W_m(\tau)\sin(m\pi r) = r. \qquad (17)$$

We find the initial conditions for them from (8). Assuming $\tau = 0$ in expressions T and U from (5) and (11), we obtain:

$$\varphi(0)r + \varphi_1(0)\left(\frac{r^3}{6} - \frac{r}{6}\right) + \sum_{m=1}^{\infty} Z_m(0)\sin(m\pi r) = 0,$$
$$\psi(0)r + \psi_1(0)\left(\frac{r^3}{6} - \frac{r}{6}\right) + \sum_{m=1}^{\infty} W_m(0)\sin(m\pi r) = r. \qquad (18)$$

Thus, we have two differential equations (14), two algebraic equations obtained from (7) taking into account (17):

$$-a_1\varphi(\tau) - \frac{1}{3}\varphi_1(\tau) - a_2\psi(\tau) + \pi\sum_{m}^{N}(-1)^{m+1} m Z_m(\tau) = h_1,$$
$$b_2\psi(\tau) + \frac{1}{3}\psi_1(\tau) + b_1\varphi(\tau) - \pi\sum_{m}^{N}(-1)^{m+1} m W_m(\tau) = h_2, \qquad (19)$$

where $h_1 = a_1 + a_2 u_p/u_0,\ h_2 = b_1 + b_2 u_p/u_0$,

and $2N$ differential equations, which are obtained from the expansion of expressions (6) taking into account (17). We multiply both equations of the system by $\sin(m\pi r)$ and integrate over r within $[0,1]$, which corresponds to the operation of expanding functions into Fourier series and we get:

$$k = 1..N: \quad \frac{(-1)^{k+1}\varphi'(\tau)}{k\pi} + \frac{(-1)^k \varphi_1'(\tau)}{k^3\pi^3} + \frac{1}{2}Z_k'(\tau) =$$
$$= A_{1,1}\left[\frac{1}{2}\pi^2 k^2 Z_k(\tau) + \frac{(-1)^k \varphi_1(\tau)}{\pi k}\right] + A_{1,2}\left[\frac{1}{2}\pi^2 k^2 W_k(\tau) + \frac{(-1)^k \psi_1(\tau)}{\pi k}\right],$$
$$k = 1..N: \quad \frac{(-1)^{k+1}\psi'(\tau)}{k\pi} + \frac{(-1)^k \psi_1'(\tau)}{k^3\pi^3} + \frac{1}{2}W_k'(\tau) = \qquad (20)$$
$$= A_{2,1}\left[\frac{1}{2}\pi^2 k^2 Z_k(\tau) + \frac{(-1)^k \varphi_1(\tau)}{\pi k}\right] + A_{2,2}\left[\frac{1}{2}\pi^2 k^2 W_k(\tau) + \frac{(-1)^k \psi_1(\tau)}{\pi k}\right].$$

The initial conditions in the form (18) must be satisfied for any r. As $r, r^3, \sin m\pi r$ – linearly independent functions, then from (18) it follows:

$$\psi(0) = 1,\ \varphi(0) = \varphi_1(0) = Z_m(0) = \psi_1(0) = W_m(0) = 0;\ m = 1 \div N. \qquad (21)$$

Let us transform the system (14), (19), (20) to the standard form by introducing the notation:

$$\varphi(\tau) = y_1(\tau),\ \psi(\tau) = y_2(\tau),\ \varphi_1(\tau) = y_3(\tau),$$
$$\psi_1(\tau) = y_4(\tau),\ Z_m(\tau) = y_{m+4}(\tau),\ W_m(\tau) = y_{m+4+N}(\tau), m = 1..N. \qquad (22)$$

In this case, system (14), (19), (20) will contain $(4+2N)$ – linear equations:

$$y_1' - A_{1,1}y_3 - A_{1,2}y_4 = 0,\ y_2' - A_{2,1}y_3 - A_{2,2}y_4 = 0,$$

$$a_1 y_1 + a_2 y_2 + \frac{1}{3} y_3 + \sum_{m=1}^{N} y_{m+4} m\pi (-1)^m = h_1,$$

$$b_1 y_1 + b_2 y_2 + \frac{1}{3} y_4 + \sum_{m=1}^{N} y_{m+4+N} m\pi (-1)^m = h_2,$$

$$\frac{(-1)^{m+1}}{m\pi} y_1' + \frac{(-1)^m}{m^3\pi^3} y_3' + \frac{1}{2} y_{m+4}' -$$

$$- A_{1,1}\left[\frac{1}{2}\pi^2 m^2 y_{m+4} + \frac{(-1)^m}{m\pi} y_3\right] - A_{1,2}\left[\frac{1}{2}\pi^2 m^2 y_{m+4+N} + \frac{(-1)^m}{m\pi} y_4\right] = 0, \qquad (23)$$

$$\frac{(-1)^{m+1}}{m\pi} y_2' + \frac{(-1)^m}{m^3\pi^3} y_4' + \frac{1}{2} y_{m+4+N}' -$$

$$- A_{2,1}\left[\frac{1}{2}\pi^2 m^2 y_{m+4} + \frac{(-1)^m}{m\pi} y_3\right] - A_{2,2}\left[\frac{1}{2}\pi^2 m^2 y_{m+4+N} + \frac{(-1)^m}{m\pi} y_4\right] = 0 .$$

We find the initial conditions for it from (21) using (22):

$$y_1(0) = y_j(0) = 0, \; y_2(0) = 1, \; j = 3 \div 4 + 2N . \qquad (24)$$

The solution of the system of equations (23) with initial conditions (24) can be obtained by the classical method. After performing the reverse renaming in accordance with expression (22), we find the functions $\varphi(\tau), \varphi_1(\tau), \psi(\tau), \psi_1(\tau), Z_m(\tau), W_m(\tau)$, $m = 1 \div N$. Finally, we obtain expressions for the desired functions:

$$T = \frac{1}{r}\left[M_z + Z_1(\tau)\sin(m\pi r)\right], \qquad U = \frac{1}{r}\left[M_w + W_1(\tau)\sin(m\pi r)\right]. \qquad (25)$$

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