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Mathematical Modeling of Drying Process of Plant Material in Drum Dryer at Variable Speed of Movement of Material

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Summary. In the system of technological operations of post-harvest handling of the crop is drying. Universal dryer drum type are widely used in farms, because, allow for dewatering of various bulk wet materials, but for a number performance indicators (specific energy consumption, automation level, implementation of environmental requirements, and others), these dryers do not quite meet the modern requirements of agricultural production and processing sectors.

The decision of problems of optimization of performance and energy consumption of drum units is possible only when adequate mathematical models of processes of heat and mass transfer taking into account the governing parameters of the process. In article on the basis of the analysis of the literature substantiates the scientific tasks of the analytical mathematical description and calculation of parameters of process of drying particulate plant material in a pneumatic drum units.

Using the methods of thermal and material balance, based on simplified representations of the processes of heat and mass transfer mathematical model describing change of parameters of the drying agent and material in the pneumatic drum unit in the process of moving along the rotational drum.

For example, analytic analysis of changes in the temperature of the drying agent and the material and its moisture content is given the solution of the equations for a linear law of transfer of material along the drum.

So as a result, the research obtained a mathematical model of stationary process of drying the plant material in a pneumatic drum unit.

The analytical dependencies describing the distribution of parameters of process of drying of the material in the drum with a given speed of movement.

Key words: modeling, process, drying, material, drum, speed.

INTRODUCTION

In the system of technological operations of post-harvest processing of crops, is important thermal drying [1, 2, 3]. Given the wide range drying products, the most versatile dryer units are pneumatic drum assemblies [4, 5, 6]. But despite the widespread use of drum dryers the theory of processes taking place in them to date is not sufficiently developed. Compatible phenomena of heat and mass transfer associated with moving the drying agent, who also is a means of transporting material. Reducing the weight of the material in the drying process leads to changes in the speed of its movement along the drum, which in current models is not considered. However, the exclusion of the arbitrariness of the speed of movement of the material and development of methods to control the speed of movement (except changing the revolutions of the drum) can significantly intensify the process of drying and to improve the quality of the product dried. In addition, the relevant issue is not only the creation and implementation of new technologies and equipment to implement thermal drying , and a reduction in financial costs for the process of development of such machines [7].

THE ANALYSIS OF RECENT RESEARCHES AND PUBLICATIONS

Recent work on the problem of drying of agricultural plant materials and products note the works [8, 9, 10].

In [8] substantiated methods for determining displacement of the material in the drum that rotates with different type of attachments, in the monograph [9] investigated heat and mass transfer in processes of drying in drum-type units with the transverse and longitudinal flow of material.

In [10] is justified based on process parameters from the design parameters of the drum. In early works [11, 12] the mathematical model of the dynamic modes of a drum dryer.

Known works [13, 14, 15] reduced to the design and analysis determine residence time of material in the drum and the exposure of drying.

Change the speed of the moving material in the drum and its influence on the performance of the process is not considered.

OBJECTIVE

The determination of regularities of the drying process on the basis of simplified model representations, and taking into account the changes of the velocity of the material coordinate movement.

THE MAIN RESULTS OF THE RESEARCH

The processes of heat and mass transfer during drying of plant materials and products in installations of pneumatic drum type describes ordinary differential equations, which are formed in the closed system of the fourth order [11, 12]:

$$\frac{r_0}{C_м}\left(\frac{\partial U}{\partial \tau}+\upsilon_м\frac{\partial U}{\partial y}\right)+\left(\frac{\partial \theta}{\partial \tau}+\upsilon_м\frac{\partial \theta}{\partial y}\right)=\frac{\alpha f}{C_м m_м}(t-\theta) \quad (1)$$

$$\frac{\partial t}{\partial \tau}+\upsilon\frac{\partial t}{\partial y}=\frac{\alpha f}{C_p m_p}(\theta-t) \quad (2)$$

$$G_0\left(\frac{\partial U}{\partial \tau}+\upsilon_м\frac{\partial U}{\partial y}\right)=\beta f\left(P_н(\theta)-P(d)\right) \quad (3)$$

$$\frac{\partial d}{\partial \tau}+\upsilon\frac{\partial d}{\partial y}=\frac{G_0}{G_p}\left(\frac{\partial U}{\partial \tau}+\upsilon_м\frac{\partial U}{\partial y}\right) \quad (4)$$

where: $m_м=V_б\cdot\psi\cdot\rho_м$ – the mass of material in the dryer, $m_p=V_б\rho$ – weight of drying agent in the drum, $V_б$ – the volume of the drum, ψ – the fill factor, $\rho_м$, ρ – the density of the material and a drying agent, $\upsilon_м$, υ – the speed of the material and a drying agent, α, β – the coefficients of heat and mass transfer, f – the surface of the material that participates in the exchange processes, C_p, $C_м$ – the heat capacity of the drying agent and material, r_0 – heat of vaporization, $P_н$, P – elasticity of saturated steam in the drying agent.

Mathematical reasoning physics equations of heat and mass transfer are the following conditions: moisture of the material is removed according to Dalton's law, the moisture in the material evaporates and is removed at the same time, the moisture content and temperature in the bulk material is distributed evenly, heat and mass transfer occurs only between the surface of the material and the drying agent, the effects of radiation and contact heat transfer coefficients are taken into account heat transfer, stationary fields of temperatures and moisture content are accepted one-dimensional, that change with the coordinate y measured in the direction of movement of the material.

The system (1)-(4) is a complete mathematical model of the drying process in pravoberezhnomu the aggregate taking into account the adopted assumptions under appropriate boundary conditions:

$$\theta(0,\tau)=\theta_1(\tau),\quad t(0,\tau)=t_1(\tau),\quad U(0,\tau)=U_1,$$

$$d(0,\tau)=d_1,\quad \theta(y,0)=\theta_0,\quad t(y,0)=t_0,$$

$$U(y,0)=U_0,\quad d(y,0)=d_0.$$

For the solution of specific objectives – determine the impact velocity of the material (static and dynamic) modes of drying system of equations have greatly simplified and divided into two stages: determination of the steady-state mode of operation of the dryer and transition. The system of equations can be greatly simplied if we make an additional assumption: the intensity of drying is proportional to the current moisture content and the rate of heating of the material and can be described by the equations:

- Lykov [18]:

$$-\frac{dU}{d\tau}=k(t)(U-U_r), \quad (5)$$

$$dU=\frac{C_м}{r_0 Rb}d\theta, \quad (6)$$

where: $k(t)$ – coefficient of drying, U_r – equilibrium moisture content, $Rb=\frac{C_м(U)d\theta}{r_0(\theta)dU}$ – criterion Rebinder.

Since the heat transfer coefficient in the drying process is reduced [19] and decreases the mass of material in the drum (due to drying), the value $\frac{\alpha f}{m_м}$ – you can take a constant (average per process), the rate of drying depends on the temperature of the drying agent. We assume that the drying coefficient is linearly dependent on temperature:

$$k(t)=a+bt \quad (7)$$

The change in the moisture content of the drying agent affects the process of moisture removal from the material [20], but with increasing moisture content of the drying agent increases the heat transfer coefficient, so the assumption $\alpha(y)=const$ – formally justified. As in rotary dryers of agricultural materials used in high-temperature drying agent $t\geq 120\ ^0C$ the material can be dried to absolutely dry matter, suggesting that the magnitude of the equilibrium moisture content constant, according to the parameters of drying agent at the outlet of the drum – $U_r=U(t_2,d_2)$.

Assumptions allow to exclude from equation (1) variable *U(y)*, and from equation (3) component, which depends on the temperature of the material $P(\theta)$ and reduce the order of the system.

Consider a stationary mode of operation of the dryer (after warm-up time) when each point of the volume of the drum all process parameters are time variables and for each coordinate by the length and the output have constant values. Equating the time derivatives to zero and considering the equations (5) and (6) we get the system of equations in ordinary derivatives:

$$\upsilon\frac{dt(t)}{dy}=\frac{\alpha f}{C_p m_p}(\theta(y)-t(y)), \quad (8)$$

$$\upsilon_м\frac{d\theta(y)}{dy}-\frac{r_0}{C_м}\upsilon_м\frac{dU(y)}{dy}=\frac{\alpha f}{C_м m_м}(t(y)-\theta(y)), \quad (9)$$

$$-\upsilon_{м}\frac{dU}{dy}=\left(a+bt(y)\right)\left(U(y)-U_{r}\right). \quad (10)$$

We introduce the notation:

$$k_1=\frac{\alpha f}{C_{м}{}' m_{м}},\; k_2=\frac{\alpha f}{C_p m_p \upsilon},\; C_{м}{}'=C_{м}\left(1-\frac{1}{Rb}\right).$$

Given the assumptions made and considering the change of the velocity of the material along a drying path, according to the reduction of mass of material passing the drum from equations (8) and (9) we get:

$$\frac{dt(y)}{dy}=k_2\left[\theta(y)-t(y)\right], \quad (11)$$

$$\frac{d\theta(y)}{dy}=\frac{k_1}{\upsilon(y)}\left[t(y)-\theta(y)\right]. \quad (12)$$

Subtract the second equation from the first:

$$\frac{d}{dy}\left[t(y)-\theta(y)\right]=-\left[\frac{k_1}{\upsilon(y)}+k_2\right]\left(t(y)-\theta(y)\right) \quad (13)$$

Where one of the first integrals of the system takes the form:

$$ln\left|t(y)-\theta(y)\right|=ln(C_1)-\int_0^y\left[\frac{k_1}{\upsilon(s)}+k_2\right]ds. \quad (14)$$

Where one of the first integrals of the system takes the form:

$$t(y)-\theta(y)=C_1\cdot exp\left(-\int_0^y\left[\frac{k_1}{\upsilon(s)}+k_2\right]ds\right). \quad (15)$$

A decision on *t(y)*:

$$t(y)=\theta(y)+C_1\cdot exp\left(-\int_0^y\left[\frac{k_1}{\upsilon(s)}+k_2\right]ds\right). \quad (16)$$

A decision on θ*(y)*:

$$\theta(y)=t(y)-C_1\cdot exp\left(-\int_0^y\left[\frac{k_1}{\upsilon(s)}+k_2\right]ds\right). \quad (16a)$$

Let us substitute the expression (16A) in equation (11) and get:

$$\frac{dt(y)}{dy}=-k_2C_1\cdot exp\left(-\int_0^y\left[\frac{k_1}{\upsilon(s)}+k_2\right]ds\right). \quad (17)$$

Its solution has the form:

$$t(y)=-k_2C_1\int_0^y exp\left(-\int_0^{\xi}\left(k2+\frac{k1}{\upsilon(s)}\right)ds\right)d\xi+C_2\;. \quad (18)$$

Substitute the obtained expression (18) into equation (16a) and get the solution of the equation:

$$\theta(y)=-k_2C_1\int_0^y \exp\left(-\int_0^{\xi}\left(k2+\frac{k1}{\upsilon(s)}\right)ds\right)d\xi+ \\ +C_2- \\ -C_1\cdot\exp\left(-\int_0^y\left[\frac{k_1}{\upsilon(s)}+k_2\right]ds\right). \quad (19)$$

Steel of integration C_1 and C_2 define the boundary conditions:

$$t(0)=t_1,$$

$$\theta(0)=\theta_1,$$

$C_2=t_1$,

$\theta_1=C_2-C_1$,

$C_1=t_1-\theta_1$.

The solution of the Cauchy problem would be:

$$\theta(y)=-k_2(t_1-\theta_1)\int_0^y \exp\left(-\int_0^{\xi}\left(k2+\frac{k1}{\upsilon(s)}\right)ds\right)d\xi+ \\ +t_1- \\ -(t_1-\theta_1)\cdot\exp\left(-\int_0^y\left[\frac{k_1}{\upsilon(s)}+k_2\right]ds\right). \quad (20)$$

$$t(y)=-k_2(t_1-\theta_1)\int_0^y \exp\left(-\int_0^{\xi}\left(k2+\frac{k1}{\upsilon(s)}\right)ds\right)d\xi+ \\ +t_1. \quad (21)$$

Take as a first approximation, a linear dependence of the rate of movement of the length of the drying path:

$$\upsilon(s)=a_1+b_1s.$$

Then:

$$-\int_0^y \left[\frac{k_1}{\upsilon(s)} + k_2 \right] ds = -\left[k_2 y + \frac{k_1}{b_1} \cdot ln \frac{a_1 + b_1 y}{a_1} \right]. \quad (22)$$

Substitute (22) into (17) and taking into account the initial conditions we get:

$$t(y) = t_1 + \frac{1}{b_1} \left[\begin{array}{l} k_2 (t_1 - \theta_1) \cdot \\ \exp\left(\frac{a_1 k_2}{b_1} \right) \\ \left(\begin{array}{l} a_1^{\frac{k_1}{b_1}} (a_1 + b_1 y)^{1 - \frac{k_1}{b_1}} \\ E_n(Z_1) - a_1 E_n(Z_2) \end{array} \right) \end{array} \right] \quad (23)$$

where: $E_n(Z_1) = \int_1^\infty \frac{e^{-Z_1 t}}{t^n} dt$

and

$E_n(Z_2) = \int_1^\infty \frac{e^{-Z_2 t}}{t^n} dt$ – exponential integrals,

$$Z_1 = k_2 \left(\frac{a_1}{b_1} + y \right),$$

$$Z_2 = \frac{a_1 k_2}{b_1},$$

$$n = \frac{k_1}{b_1}.$$

Substituting equation (22) and derive an equation for the temperature of the drying agent in (16A), we get:

$$\theta(y) = t_1 + \frac{1}{b_1} \left[\begin{array}{l} k_2 (t_1 - \theta_1) \cdot \exp\left(\frac{a_1 k_2}{b_1} \right) \\ \left(\begin{array}{l} a_1^{\frac{k_1}{b_1}} (a_1 + b_1 y)^{1 - \frac{k_1}{b_1}} E_n(Z_1) - \\ - a_1 E_n(Z_2) \end{array} \right) \end{array} \right] - $$
$$-(t_1 - \theta_1) \times \quad (24)$$
$$\times \exp\left(-k_2 y - \frac{k_1}{b_1} \cdot \ln \frac{a_1 + b_1 y}{a_1} \right).$$

Substituting values of temperature *t(y)* in equation (10) after separation of variables get:

$$U(y) = U_r - (U_1 - U_r) \cdot$$
$$\exp \left[\int_0^y \left[\begin{array}{l} \frac{1}{a_1 + b_1 y} \\ \left(a + b \cdot \left(\begin{array}{l} t_1 + \\ + \frac{1}{b_1} \left[\begin{array}{l} k_2 (t_1 - \theta_1) \cdot \\ \exp\left(\frac{a_1 k_2}{b_1} \right) \times \\ \times \left(\begin{array}{l} a_1^{\frac{k_1}{b_1}} (a_1 + b_1 y)^{1 - \frac{k_1}{b_1}} \\ E_n(Z_1) - \\ - a_1 E_n(Z_2) \end{array} \right) \end{array} \right] \end{array} \right) \right) \end{array} \right] dy \right] \quad (25)$$

Thus the resulting equation (23), (24), (25) determine the temperature distribution and the moisture content of the material during the drying process in a rotating drum when the speed of movement.

CONCLUSIONS

1. A mathematical model of stationary process of drying the plant material in pneumatic drum unit.
2. The analytical dependencies describing the distribution of parameters of process of drying of the material in the drum with a given speed of movement.-size range of mobile agricultural energy products.

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МАТЕМАТИЧЕСКОЕ МОДЕЛИРОВАНИЕ ПРОЦЕССА СУШКИ РАСТИТЕЛЬНОГО МАТЕРИАЛА В БАРАБАННОЙ СУШИЛКЕ ПРИ ПЕРЕМЕННОЙ СКОРОСТИ ПЕРЕМЕЩЕНИЯ МАТЕРИАЛА

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Аннотация. В системе технологических операций послеуборочной обработки урожая сельскохозяйственных культур важное место занимает сушки. Универсальные сушилки барабанного типа широко используются в хозяйствах, поскольку позволяют проводить обезвоживание различных сыпучих влажных материалов, но по целому ряду показателей работы (удельные затраты энергии, уровень автоматизации, выполнения экологических требований, и другие) эти сушилки не совсем соответствуют современным требованиям производства сельскохозяйственной и перерабатывающей отраслей.
Решение задач оптимизации по производительности и энергозатратам барабанных агрегатов возможно только при наличии адекватной математической модели процессов тепло- и массообмена с учетом определяющих параметров процесса. В статье на основе анализа литературных источников обоснованно научную задачу аналитического математического описания и расчета определяющих параметров процесса сушки растительных дисперсных материалов в пневмобарабанних агрегатах.
С помощью методов теплового и материального баланса на основе упрощенных представлений о процессах тепло- и массообмена построена математическая модель, описывающая изменение параметров сушильного агента и материала в пневмобарабанном агрегате в процессе перемещения вдоль вращательного барабана.
На примере аналитического анализа изменения температуры сушильного агента и материала и его влагосодержания приведены решение полученных уравнений для линейного закона перемещения материала вдоль барабана.
Таким образом в результате выполненного исследования получена математическая модель стационарного процесса сушки растительного материала в пневмобарабанном агрегате.
Определены аналитические зависимости, описывающие распределение параметров процесса сушки материала в барабане с учетом скорости перемещения.

Ключевые слова: модерирование, процесс, сушка, материал, барабан, скорость.