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ANALYZING THE KINETICS IN THE FILTRATION DRYING OF CRUSHED COTTON STALKS

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The drying of crushed plant-derived materials, in particular crushed cotton stems, is a complex heat-exchange and technological task. Resolving this task successfully ultimately determines the specific energy costs of the drying process and the quality of the resulting products. The rational drying regime of crushed cotton stems should ensure the minimum possible process duration, energy costs, and provide the necessary quality characteristics of the dried material. To address this issue, it is necessary to investigate the influence of technological parameters of the process (the temperature and filtration rate of the heat agent), as well as the thickness of the stationary layer of crushed cotton stems, on drying kinetics.

This paper has generalized experimental studies into the kinetics of filtration drying of crushed cotton stems during the period of complete saturation of the thermal agent with moisture.

The influence of the temperature of the drying agent, the speed of its filtering through a stationary layer of different heights of wet crushed cotton stems, on the kinetics of filtration drying has been shown. The study's results demonstrate the dynamics of moisture removal at different parameters of the heat agent and the heights of the stationary layer of crushed cotton stems.

The resulting dependence $\eta = 3.3 \cdot 10^{-4} t^{0.54} \cdot v_0^{2.8}$, *has been established, which is used to determine the value of the kinetic coefficient* η *for crushed cotton stems; the value of the kinetic coefficient has been calculated, a=20.74 1/m. The dependence* $\frac{w^c}{w_0^c} = 1 - 3.3 \cdot 10^{-4} t^{0.54} \cdot v_0^{2.8} \cdot \tau \cdot e^{-20.74 \cdot H}$, *has been derived, using which makes it possible to generalize the kinetics of filtration drying of crushed cotton stems during the period of complete saturation of the heat agent with moisture within the limits of changing the moisture content of the veneer* $w_0^d \geq w^d \geq w_{cr}^d$.

The comparison of the experimental data with those obtained theoretically has shown that the maximum absolute value of relative error does not exceed 15.2 %

Keywords: cotton stalks, kinetics, filtration drying, relative humidity, pressure loss, stationary layer, fibrous particles

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1. Introduction

When processing raw cotton, cotton cultivation waste is dominant. Most of it is the stems and roots of plants of this technical crop [1]. Cotton stalks (guza-paya), the volume of formation of which annually is more than 0.5 million tons, are a very promising raw material for recycling in order to obtain building materials. A relatively small part of this waste is used by the population for household needs as fuel. Other attempts to recycle guza-paya have not been successful for any large-scale practical application. Often, these wastes are burned directly in the fields or processed using thermochemical processes, such as pyrolysis, for the purpose of energy recovery, as shown by the authors of [2, 3].

Studies on the use of cotton stalks as solid biofuels are extremely important in terms of reducing the anthropogenic impact on the environment. The rational use of cotton stalks could save a significant amount of fossil energy sources, and, accordingly, reduce the amount of carbon dioxide emissions into the atmosphere. In order to increase the specific heat of combustion of cotton stalks, they must be crushed, dried to the final moisture content of 0.1–0.12 kg H_2O/kg dried material and, accordingly, granulated or briquetted. The main costs during the manufacture of granules or briquettes are related to the drying process. Therefore, theoretical and experimental studies into the kinetics of filtration drying of crushed cotton stalks are of relevance both scientifically and practically.

2. Literature review and problem statement

Numerous studies have established that one of the ways of rational utilization of agricultural waste is to use it as binders for asphalt mixtures [4]. As thermal insulation and structural building material [5], the outer crust is fibrous and can be used as a source of fibers [6]. Paper [7] considers the potential production of energy from cotton stalks by burning, hydrothermal carbonation, fermentation, and anaerobic fermentation technologies. Previous studies on this issue [1–8] have mainly solved the problem of obtaining such materials. However, there are no detailed studies on the processing and disposal of guza-paya, which makes it difficult to predict the long-term preservation of its quality [9].

In this regard, studies [10, 11] have considered, from a single theoretical position, the feasibility of using materials based on cotton stalks and confirmed it experimentally. This is proven by studies into the physicochemical foundations of their structure formation, as well as the physical-technical, including thermophysical, properties.

When processing, all materials and products are subjected to drying, which largely determines the quality of products, the economy and environmental safety of production. At the same time, studying the physical mechanism and kinetic features of drying processes is of particular importance [12]. Without such results, improvement of drying processes and equipment is impossible, and, therefore, the specified issue is relevant and has great practical importance. Such studies are of scientific interest since the methodological commonality of the problems of heat and mass transfer that arise is characteristic of many processes in various industries and natural science.

When designing drying equipment, it is necessary to comply with the following requirements: the structure of the equipment should ensure uniform heating and drying of the product with reliable control over its temperature and humidity; in addition, the drying equipment should have less metal consumption. When choosing the type and design of an industrial dryer, one should first take into consideration the following points: working volume, the principle of operation, the type of drying agent, power consumption per cycle, productivity, the ability to improve, and the availability of additional options [12].

The high energy intensity of the process leads in general in the drying industry to significant energy costs. The consequence of the latter is also a decrease in the ecological purity of both the technological process of drying and the dried materials obtained with the help of convection technologies.

One of the high-intensity methods of removing both free and bound moisture is filtration drying. This is due to the fact that during filtration drying, the heating agent is filtered through the porous structure of the wet material. When implementing the drying of materials by filtration method, the filtration of the drying agent through a layer of material provides the best conditions for interphase heat and mass exchange since each particle is washed with a gas flow [12]. Therefore, the rate of heat and mass transfer processes during filtration drying of dispersed materials is higher compared to traditional methods, which makes it possible to reduce the duration of drying and reduce energy consumption. In addition, during filtration drying, a low-temperature thermal agent is used, which makes it possible to reduce the energy consumption of heating the material. To design installations for the filtration drying of fibrous materials that provide the lowest energy consumption for implementing the process, it is necessary to study the kinetic features of the drying process of the selected material [13].

The kinetics of the drying process in the generally accepted variant determines the change in the moisture content of the material over time. The kinetic features of the processes of drying materials are largely influenced by the properties of wet materials parameters of the heating agent, the state of the material in the drying zone. The study of drying kinetics is necessary primarily for solving practical tasks. The subject of research is the problem of the speed and duration of drying wet materials. The kinetics of drying wet materials has been investigated experimentally, by building the drying curve and heating curve [12, 13].

In [14], a method of numerical modeling was used to describe the process of heating, drying, and pyrolysis of large particles of wood found in furnaces. To maintain a high degree of flexibility and independence of specific material properties, kinetics, particle sizes and shapes, this method is based on a set of one-dimensional and transitional conservation differential equations for mass and energy. The authors of [15] proposed a numerical calculation method for modeling the simultaneous drying and pyrolysis of wood and biomass. Work [16] investigated the process of drying the "black alkali", a by-product of the pulp and paper industry. The process was carried out in the atmosphere of nitrogen, and at a temperature of 20 to 300 °C. The kinetic of drying, in this case, is simulated using five semi-empirical models since volatile substances are also released along with moisture from the "black alkali". The kinetics of low-temperature drying of softwood were examined in [17]. The kinetics, in this case, takes into consideration the classical stages of drying (pseudo-isenthalpic mode, the first and second periods of falling drying speed). However, the process models described in [14–17] cannot be used to describe the kinetics of filtration drying of crushed cotton. Paper [18] investigates the kinetics of filtration drying of iron sulfate (II) heptahydrate at different heights of the material layer and pressure drops over dry material, that is, at different speeds of movement of the thermal agent. The authors of [19] determined the diffusion coefficient during grain filtration drying, based on the solution to differential equations under the boundary conditions of the first kind. Paper [20] reports the results of experimental studies into the kinetics of filtration drying of corn bards, which has previously proven effective in drying other crops and various dispersed materials. The reported results have been analyzed; the changes occurring on the filtration drying curves depending on the change in the height of the material layer and the temperature of the heating agent have been described. The dependences obtained by the authors could be used only to predict the kinetics of filtration drying of the materials studied in those works, which are characterized by a certain shape and structural structure of particles. However, the results of the studies reported in [17–20] relate to specific materials, so their application to other materials that differ in structural structure and shape of particles is impossible due to a large error between experimental and theoretically calculated values. No experimental or theoretical studies into the kinetics of filtration drying of crushed cotton stalks were found in the available literature. Currently, crushed cotton stalks are dried in drum dryers, which are bulky and ineffective in terms of heat energy costs. In drum drying plants, the material is crushed to form a finely dispersed fraction, which tends to self-heat at a temperature of the thermal agent of 200–300 °C. In addition, drying drums require cleaning exhaust gases from finely dispersed particles in cyclones and fabric filters, which requires additional capital costs for equipment. Therefore, cotton stalks are mainly burned at the site of their cultivation. The use of the filtration method of drying could significantly improve the efficiency of the drying process by ensuring high coefficients of heat and mass exchange in the stationary layer and the use of a low-temperature heat agent. Given that the drying process proceeds in a stationary layer, particle grinding does not occur, therefore, there is no need to use cleaning equipment, which, in turn, reduces the cost of the finished product.

3. The aim and objectives of the study

The aim of this work is to establish the main patterns of filtration drying of crushed cotton stalks. This could reduce energy costs and negative impact on the environment.

To accomplish the aim, the following tasks have been set:

– to theoretically analyze the kinetics of drying wet materials;

– to experimentally investigate the kinetics of filtration drying of crushed cotton stalks at different temperatures and filtration speeds of the heating agent, as well as at different heights of the stationary layer;

– to derive estimation dependences for calculating the change in moisture content in time and the time of filtration drying of crushed cotton stalks in the period of full and partial saturation of the heating agent with moisture;

– to compare experimental data with theoretically calculated data and establish the value of relative error.

4. The study materials and methods

The object of drying was crushed cotton stalks, which are agricultural waste that accumulates in significant quantities; the task of their recycling is solved only partially while they have a wide range of uses.

Before the start of research into the kinetics of filtration drying of crushed cotton stalks, we determined the initial humidity of the material under study using ADGS60G (AXIS), the accuracy class according to DSTU EN 45501-II. The specified temperature of the heating agent was set using the electronic thermostat SESTOS D1S (China). The flow rate of the heating agent was determined using a regulating valve, which was measured using a rotameter.

The formation of a layer of material of proper height was carried out in container 1, schematically shown in Fig. 1. To ensure the identical conditions for the experiment, we calculated, based on the known bulk density of the material, the diameter of the container, and the required height of the layer, the mass of crushed cotton stalks. The batch of the material was loaded into the container in such a way that the height of the material layer corresponds to the calculated one. That ensured the same differentness in the material in each experiment.

A fan and a heater were turned on for the experiment. After setting the predefined temperature, which was regulated using the electronic thermostat SESTOS D1S, we turned on the vacuum pump.

Container 1 with a layer of wet material was placed on receiver 2; locking valve 5 was opened; the drying process was carried out while we determined a change in the mass of the material at certain intervals by a weight method. For weighing, we used the electronic scales AXIS-AD3000 (Poland); the weighing time was no more than 10–15 s. Drying lasted until the material reached a stable mass.

The kinetics of the filtration drying of crushed cotton stalks of different heights of the stationary layer of different costs and temperatures of the heating agent and the same initial average moisture content were investigated. The average initial moisture content of crushed cotton stalks was 0.46 kg H_2O/kg dried material, which is due to the presence in the crushed particle of free (capillary) and bound moisture. Free moisture is contained in cell cavities and intercellular gaps, and the bound – in cell walls. The process of filtration drying was investigated until the equilibrium with the thermal agent of moisture content was achieved w_p^c.

Experimental studies were carried out at the following values: fictitious filtering speed of the thermal agent, 0.91÷2.17 m/s; the temperature of the heating agent, 40÷80 °C; and the height of the stationary layer of crushed cotton stalks, 40÷120 mm. The selected limits of temperature change, the speed of the heating agent, and the height of the stationary layer are due to the need to ensure the minimum possible energy costs for the process of drying crushed cotton stalks in industrial production.

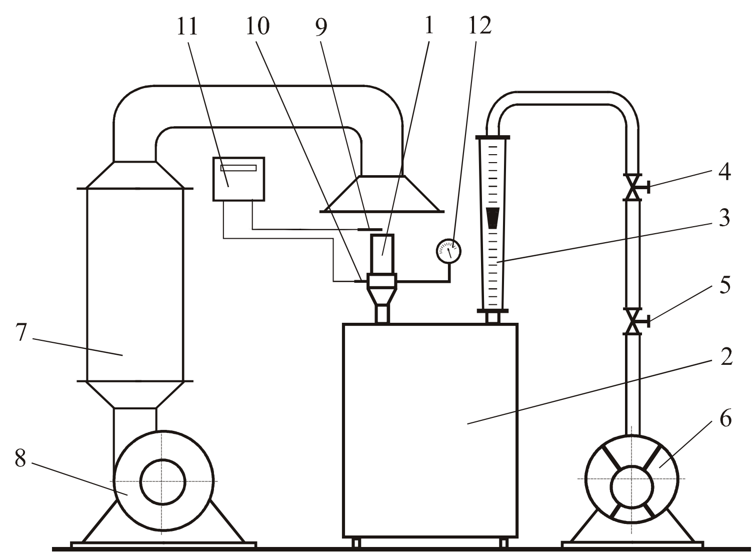

Fig. 1. Diagram of experimental installation: 1 — container; 2 — receiver; 3 — rotameter; 4, 5 — shut-off and adjusting valves; 6 — water ring vacuum pump; 7 — calorifier; 8 — fan; 9, 10 — thermocouples; 11 — measuring instrument; 12 — vacuum meter

5. Results of studying the kinetics of filtration drying of crushed cotton stalks

5. 1. Theoretical analysis of filtration drying kinetics

For the filtration process of drying crushed cotton stalks, based on the physical characteristics of its progress, a model of ideal displacement can be used, given in work [21]; the Péclet number is Pe>>1.

For a mathematical notation of the kinetics of filtration drying of the material during the period of complete saturation of the heating agent with moisture, we use a system of differential equations of the material balance of moisture and kinetics of drying [21], which holds for 0<φ<1:

$$\begin{cases} \frac{\partial \varphi}{\partial H} = a \cdot (1-\varphi); \\ -\frac{\partial w^c}{\partial \tau} = n \cdot (1-\varphi), \end{cases} \tag{1}$$

where φ is the relative humidity, in shares;

H is the thickness of sheet material, m;

w^c is the running moisture content of the material, kg H_2O/kg dried material;

a is the kinetic coefficient, 1/m, which does not depend on the parameters of the process but depends only on the structure of the material and is calculated from the formula:

$$a = \frac{B \cdot \bar{m} \cdot \bar{n}}{0.622 \cdot P_s}, \tag{2}$$

where

$$\bar{m} = \frac{\rho \cdot F}{100 \cdot M};$$

$$\bar{n} = \bar{S} \cdot \bar{\beta} \cdot P_s;$$

B is the barometric pressure, Pa;

P_s is the saturated steam pressure, Pa;

ρ is the density of the heating agent, $\frac{\text{kg}}{\text{m}^3}$;

F is the area of the cross-section of the container, m^2;

M is the mass speed of the heating agent, $\frac{\text{kg}}{\text{s}}$;

$\bar{S}$ is the inner surface of all particles of crushed cotton stalks washed by the heating agent, m^2;

β is the mass exchange coefficient, $\frac{\text{kg H}_2\text{O}/\text{kg d. m.}}{\text{s} \cdot \text{m}^2 \cdot \text{Pa}}$.

Then, dependence (2) that takes into consideration the expressions for calculating m and n can be written as:

$$a = \frac{F \cdot B \cdot \rho \cdot \bar{S} \cdot \beta}{62.2 \cdot M}. \tag{3}$$

Solving the system of equations (1) makes it possible to build a dependence that describes the kinetics of filtration drying of crushed cotton stalks during the period of complete saturation of the heating agent with moisture until the critical moisture content w_{cr} is reached by crushed cotton stalks:

$$\frac{w^c}{w_0^c} = 1 - \eta \cdot \tau \cdot e^{-a \cdot H}, \tag{4}$$

where

$$\eta = \frac{\bar{S} \cdot \beta \cdot P_s \cdot (1-\varphi_0)}{w_0^c}. \tag{5}$$

Equation (4) can be represented as:

$$\frac{1 - \frac{w^d}{w_0^d}}{\tau} = \eta \cdot e^{-a \cdot H}. \tag{6}$$

Denote

$$\frac{1 - \frac{w^d}{w_0^d}}{\tau} = y,$$

then,

$$y = \eta \cdot e^{-a \cdot H}. \tag{7}$$

Upon transforming equation (7) logarithmically, we obtain:

$$\ln(y) = \ln(\eta) - a \cdot H \cdot \ln(e),$$

or

$$\ln(y) = \ln(\eta) - a \cdot H. \tag{8}$$

To describe the kinetics of the process of filtration drying of crushed cotton stalks, it is necessary, by using equation (4), to determine the kinetic coefficients "η" and "a", which are defined experimentally, by constructing a graphical dependence $\ln(y)=f(H)$. Using the graphical dependence, the value of the kinetic coefficient "a" is defined as the tangent of the angle of inclination of the straight line to the abscissa axis, and the value of $\ln(y)$ – by the segment that the straight line directly cuts off along the axis of the ordinate, from where the values of the coefficient "η" are found.

Equation (4) is solved relative to "η"

$$\eta = \frac{1 - \frac{w^c}{w_0^c}}{\tau \cdot e^{-a \cdot H}}. \tag{9}$$

To determine the values of the critical moisture content w_{cr} and the critical time τ_{cr} at different temperatures and filtration speeds of the heating agent, one can use the method described in [22], which involves the construction of kinetic curves:

$$\lg(w^c - w_p^c) = f(\tau),$$

where w^c, w_p^c are, respectively, the running and equilibrium value of the moisture content of the material, H_2O/kg dried material;

τ – drying time, s.

During the period of full saturation of the heating agent with moisture, the change in the humidity of the material is limited by external drying conditions – the speed of movement and the temperature of the heating agent. Therefore, "η" can be represented in general form by the following equation:

$$\eta = A \cdot t^m \cdot v_0^n. \tag{10}$$

The coefficient "A" and the indicators of powers in "m", "n" of equation (10) are determined on the basis of a generalization of the results from experimental studies conducted at different drying parameters of crushed cotton stalks and are constant for a given material.

Thus, the kinetic equation (4), taking into consideration dependence (10), can be presented in the following form:

$$\frac{w}{w_0} = 1 - A \cdot t^m \cdot v_0^n \cdot \tau \cdot e^{-a \cdot H}. \quad (11)$$

The resulting equation (11) could predict the kinetics of the filtration drying of crushed cotton stalks during the period of complete saturation of the heat agent with moisture within the change in the moisture content of crushed cotton stalks

$$w_0^d \geq w^d \geq w_{cr}^d.$$

Generalization of drying kinetics in the period of partial saturation of the heating agent with moisture was carried out according to equation [22]:

$$-\frac{dw^d}{d\tau} = K \cdot \left(w^d - w_r^d\right), \quad (12)$$

where K is the drying coefficient, 1/s, which can be represented as:

$$K = \chi \cdot N, \quad (13)$$

where χ is the relative drying factor, H_2O/kg dried material;

N is the drying speed during the period of full saturation of the heating agent with moisture, H_2O/kg dried material.

By integrating equation (12), we obtain the following equation:

$$\frac{w^d - w_e^d}{w_{cr}^d - w_e^d} = e^{-K \cdot (\tau - \tau_{cr})}. \quad (14)$$

Given that $K = \chi \cdot N$, equation (14) can be written as:

$$\frac{w^d - w_e^d}{w_{cr}^d - w_e^d} = e^{-\chi \cdot N \cdot (\tau - \tau_{cr})}. \quad (15)$$

Upon transforming equation (14) logarithmically, we obtain:

$$\ln \frac{w^d - w_p^d}{w_{cr}^d - w_e^d} = -K \cdot \left(\tau - \tau_{cr}\right). \quad (16)$$

To find the drying factor K, it is necessary to build a graphical dependence in the following coordinates

$$\ln\left(\left(w^d - w_e^d\right) / \left(w_{cr}^d - w_e\right)\right) = f\left(\tau - \tau_{cr}\right),$$

from which a given coefficient is defined as the tangent of the angle of inclination of the straight line to the abscissa axis.

To summarize the kinetics of the process of the filtration drying of crushed cotton stalks during the period of partial saturation of the heating agent with moisture, taking into consideration $K = \chi \cdot N$, it is necessary to calculate the drying speed during the period of full saturation of the heating agent with moisture N and determine the relative drying factor χ.

The drying speed during the period of complete saturation of the heating agent with moisture can be determined from the following equation:

$$N = \frac{w_0^d - w_{cr}^d}{\tau_{cr}} = \frac{\left(w_0^d - w_{cr}^d\right) \cdot \eta \cdot e^{-a \cdot H}}{1 - w_{cr}^d / w_0^d}. \quad (17)$$

To determine the relative drying coefficient χ, experimental data must be represented as a dependence $K = f(N)$ from which the value of χ is defined as the tangent of the angle of inclination of the straight line to the abscissa axis.

Equation (15) can be represented as:

$$w^d = \left(w_{cr}^d - w_e^d\right) \cdot e^{-\chi \cdot N \cdot (\tau - \tau_{cr})} + w_e^d. \quad (18)$$

Since $\tau_{cr} = f\left(w_{cr}^d\right)$, $\tau_{cr.} = \frac{w_0^d - w_{cr}^d}{N}$ (based on equation (17)), then equation (18) can be written as:

$$w^d = \left(w_{cr}^d - w_e^d\right) \cdot e^{-\chi \cdot N \cdot \left(\tau - \frac{w_0^d - w_{cr}^d}{N}\right)} + w_e^d. \quad (19)$$

Consequently, dependences (18), (19) make it possible to summarize the results of experimental studies, namely, to calculate the change in moisture content of crushed cotton stalks in time during the period of partial saturation of the heating agent with moisture until the material reaches equilibrium moisture content.

To design equipment for the implementation of filtration drying of crushed cotton stalks, it is important to determine the drying time. The time over which crushed cotton stalks achieve critical humidity can be determined by giving dependence (4) in another form and accepting $w^d = w_{cr}^d$, and $\tau = \tau_{cr}$:

$$\tau_{cr} = \frac{\left(1 - \frac{w_{cr}^d}{w_0}\right)}{\eta \cdot e^{-a \cdot H}}. \quad (20)$$

Dependence (20), taking into consideration dependence (10), by performing a series of algebraic transformations, can be represented as follows:

$$\tau_{cr} = \frac{w_0^d - w_{cr}^d}{w_0^c \cdot A \cdot t^n \cdot v_0^m \cdot e^{-a \cdot H}}, \quad (21)$$

and drying time in the period of partial saturation of the heating agent with moisture according to the following dependence:

$$\tau_{II} = \frac{1}{\chi \cdot N} \cdot \left[1 + \ln \chi \cdot \left(w^d - w_{cr}^d\right)\right]. \quad (22)$$

The total time of the filtration drying of crushed cotton stalks from the initial moisture content to the final one can be calculated according to the following dependence:

$$\tau = \tau_I + \tau_{II} = \frac{w_0^d - w_k p^d}{w_0^d \cdot A \cdot t^n \cdot v_0^m e^{-a \cdot H}} + \frac{1}{\chi \cdot N} \cdot \left(1 + \ln \chi \left(w^d - w_{cr}^d\right)\right). \quad (23)$$

The relative error between the calculated and experimental values was determined from the following formula [12]:

$$\Delta = \left| \frac{X_e - X_m}{X_e} \right|, \quad (24)$$

Δ is the value of the relative error;

X_m is the calculated value;

X_e is the average experimental value.

5. 2. An experimental study into the kinetics of the filtration drying of crushed cotton stalks

The results of our experimental studies into the kinetics of the filtration drying of crushed cotton stalks at different temperatures and filtration speeds of the heating agent, as well as at different heights of the stationary layer, are shown in Fig. 2–4.

Fig. 2 illustrates the kinetics of the filtration drying of crushed cotton stalks at different filtration speeds of the heating agent.

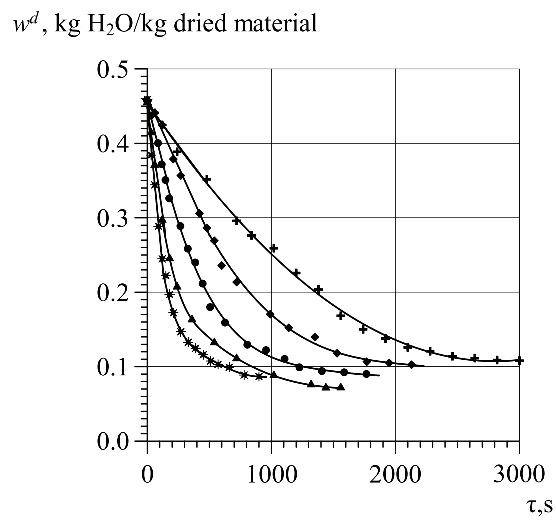

Fig. 2. Kinetics of the filtration drying of crushed cotton stalks at different speeds of movement of the heat agent: H=100 mm; t=60 °C; ✚ – v_0=0.91 m/s; ◆ – v_0=1.25 m/s; ● – v_0=1.71 m/s; ▲ – v_0=1.94 m/s; ✶ – v_0=2.17 m/s

Fig. 3 shows the kinetics of the filtration drying of crushed cotton stalks at different temperatures of the heating agent.

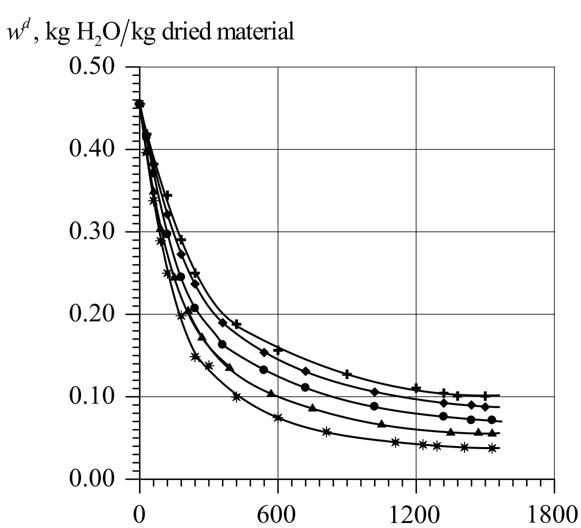

Fig. 3. Kinetics of the filtration drying of crushed cotton stalks at different temperatures of the heat agent: H=100 mm; v_0=1.94 m/s; ✚ – t=40 °C; ◆ – t=50 °C; ● – t=60 °C; ▲ – t=70 °C; ✶ – t=80 °C

Fig. 4 demonstrates the kinetics of the filtration drying of crushed cotton stalks at different heights of the stationary layer.

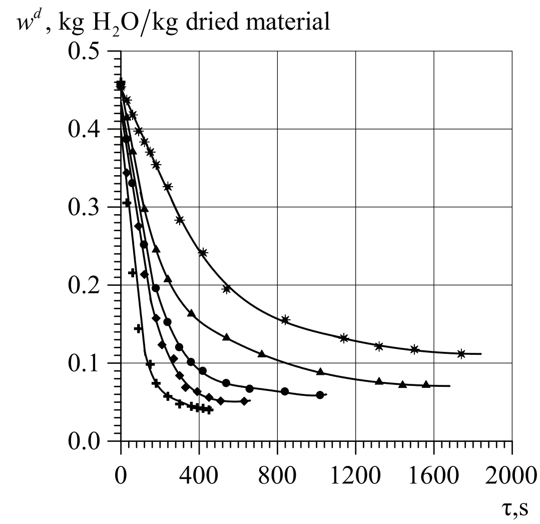

Fig. 4. Kinetics of the filtration drying of crushed cotton stalks at different heights of the stationary layer: H=100 mm; v_0=1,94 m/s; ✶ – t=40 °C; ◆ – t=50 °C; ● – t =60 °C; ▲ – t=70 °C; ✚ – t=80 °C

Generalizing the results of investigating the kinetics of the filtration crushed cotton stalks and determining kinetic coefficients makes it possible to calculate the main dimensions of the drying plant, to justify the optimal technological parameters of the process depending on the required performance.

The graphic dependences in Fig. 2–4 show that the kinetic curves of the filtration drying of crushed cotton stalks are characterized by 2 pronounced periods. The first is the period of complete saturation of the heating agent with moisture; the second period is partial saturation of the heating agent with moisture, so we generalized research results in accordance with kinetic dependences (22), (23).

5. 3. Generalizing the experimental studies into the kinetics during the periods of full and partial saturation of the heating agent with moisture

To generalize the kinetics according to the proposed dependences, it is necessary to determine the critical moisture content w_{cr} and the critical time τ_{cr}; to that end, we used the above procedure, which implies the construction of kinetic curves in the coordinates $\lg(w-w_p)=f(\tau)$. The results of studying the kinetics of the filtration drying of crushed cotton stalks were represented in the form of graphic dependences in the corresponding coordinates, which are shown in Fig. 5–7.

The graphic dependences in Fig. 5–7 show that the periods of full and partial saturation of the heating agent with moisture can be summarized by straight lines. The ordinate of their intersection would correspond to the critical moisture content $\lg w_{cr}^d$, the abscissa – to the critical time τ_{cr}, that is, the drying time of crushed cotton stalks during the period of complete saturation of the heating agent with moisture. The values of critical moisture content were calculated according to the following dependence:

$$w_{cr}^d = 10^x + w_e^d, \tag{25}$$

where x is the ordinate of the intersection point of two lines corresponding to the periods of full and partial saturation of the heating agent with moisture.

To use dependence (25), it is necessary to have a value of the equilibrium moisture content of crushed cotton stalks w_p^c. The equilibrium moisture content in the temperature range at which the study was conducted $w_p^c = f(\tau)$, was determined experimentally. It is 0.03 kg H_2O/kg dried material.

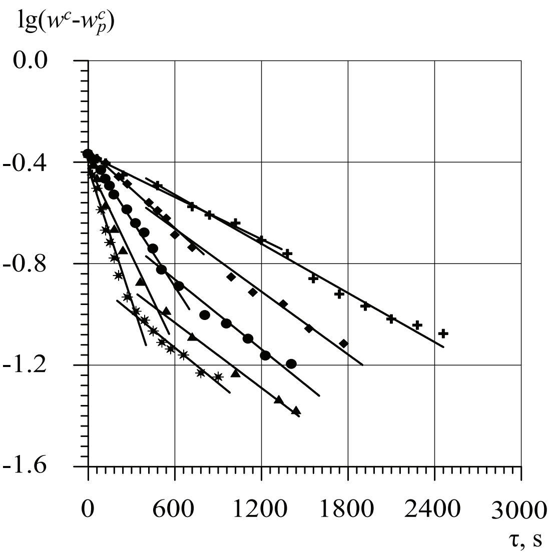

Fig. 5. Determining the critical moisture content at different filtration speeds of the heat agent: H=100 mm; t=60 °C; ✚ – v_0=0.91 m/s; ◆ – v_0=1.25 m/s; ● – v_0=1.71 m/s; ▲ – v_0=1.94 m/s; ✱ – v_0=2.17 m/s

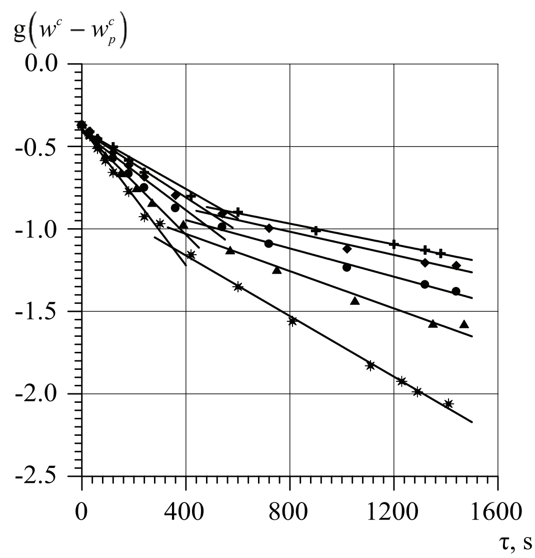

Fig. 6. Determining the critical moisture content at different temperatures of the heat agent: H=100 mm; v_0=1.94 m/s; ✚ – t=40 °C; ◆ – t=50 °C; ● – t=60 °C; ▲ – t=70 °C; ✱ – t=80 °C

Analysis of Table 1 reveals that the critical moisture content of crushed cotton stalks depends on both the temperature and filtration rate of the heating agent and the height of the stationary layer. This is because filtration drying is zonal in nature and the movement of the heat and mass exchange zone depends on both the technological parameters of the heating agent and the height of the layer of wet material.

In order to describe the kinetics of the filtration drying of crushed cotton stalks during the period of full saturation of the heating agent with moisture, we used equation (14) to determine the kinetic coefficients a and η. These coefficients are determined from experimental data by constructing a graphical dependence in coordinates $\ln\left(\left(1 - w^c / w_0^c\right)/\tau\right) = f(H)$ (Fig. 8).

Fig. 5–7 helped us establish the critical moisture content and the time of its achievement. The results are given in Table 1.

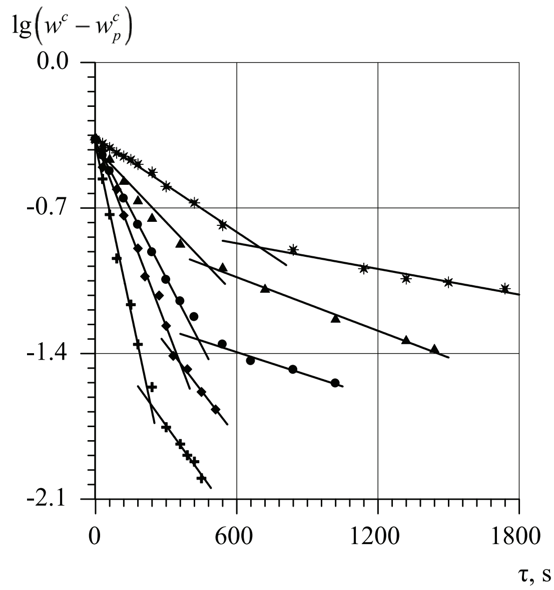

Fig. 7. Determining the critical moisture content at different heights of the stationary layer of crushed cotton stalks (designations correspond to Fig. 4): H=100 mm; v_0=1.94 m/s; ✱ – t=40 °C; ◆ – t=50 °C; ● – t=60 °C; ▲ – t=70 °C; ✚ – t=80 °C

Table 1

The value of critical moisture content w_{cr}^d and the time of reaching it τ_{cr}

H, mm	v_0, m/s	t, °C	lg(w–w_p)	w_{cr}^d	τ_{cr}
40	1.94	60	–1.54	0.059	220
60			–1.43	0.067	360
80			–1.26	0.085	420
100			–0.98	0.135	480
120			–0.89	0.159	690
100	0.91		–0.62	0.270	900
	1.25		–0.77	0.200	800
	1.71		–0.94	0.145	660
	1.94		–0.98	0.135	480
	2.17		–1.01	0.128	360
	1.94	40	–0.9	0.156	558
		50	–0.92	0.150	518
		60	–0.98	0.135	480
		70	–1.04	0.121	400
		80	–1.11	0.108	358

Analysis of Fig. 8 reveals that all experimental points at different heights of the stationary layer of crushed cotton stalks, the temperature and filtration rate of the heating agent can be fitted to straight lines. In addition, all lines that are shown in Fig. 8 are parallel to each other.

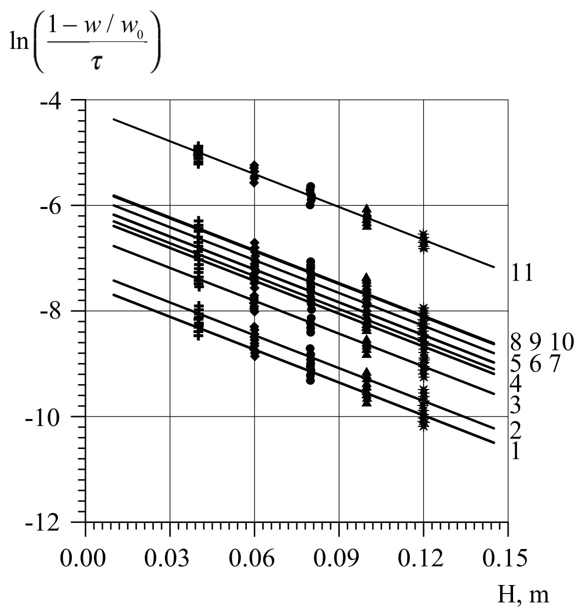

Fig. 8. Graphical dependence to determine the coefficients "a" and "η" during the period of full saturation of the heating agent with moisture

Based on the tangents of the angle of inclination of straight lines to the abscissa axis, we determine the values of the kinetic coefficient, which are the same and, accordingly, the value of the kinetic coefficient is a=20.74 1/m. The constancy of the value of the kinetic coefficient "a" for crushed cotton stalks can also be explained taking into account dependence (3), that is, increasing the mass velocity of the heating agent M leads to an increase in the mass transfer coefficient β. That determines the constancy of the β/M ratio, which does not contradict the physical essence of the drying process. The values of the kinetic coefficients "η" are also determined from Fig. 8 at the intersection of straight lines with the ordinate axis. The increase in the values of the kinetic coefficient "η" during the increase in the temperature and filtration rate of the heating agent indicates the intensification of the process of the filtration drying of crushed cotton stalks. The results of determining the coefficients "η" and "a" are given in Table 2.

Table 2

Dependence of kinetic coefficients η and a on process parameters

Line No.	t, °C	v_0, m/s	a, 1/m	lg(η)	η, 1/s
1	60	0.91	20.74	–5.42358	0.004411
2	60	1.25		–5.16442	0.005716
3	60	1.71		–4.49711	0.011141
4	60	1.94		–4.16319	0.015558
5	40	1.94		–4.10816	0.016438
6	50	1.94		–4.04016	0.017595
7	60	1.94		–3.89843	0.020274
8	70	1.94		–3.74898	0.023542
9	60	2.17		–3.56428	0.028317
10	80	1.94		–3.52793	0.029366

To determine the unknown coefficients "A", the powers of "m" and "n" in equation (10), we shall build a system of three equations, solving which would make it possible to find these unknown values.

$$\begin{cases}\eta_1 = A\cdot t_1^m\cdot v_{01}^n,\\ \eta_2 = A\cdot t_2^m\cdot v_{02}^n,\\ \eta_3 = A\cdot t_3^m\cdot v_{03}^n.\end{cases} \tag{26}$$

In each equation of the system, the values of the temperature and filtration speed of the heating agent correspond to the parameters at which the filtration drying of crushed cotton stalks was carried out. The values of the coefficients "η_1", "η_2" and "η_3" were determined from equation (9).

In order to solve the system of equations (26), it was represented in the logarithmic form:

$$\begin{cases}\ln\eta_1 = \ln A + m\cdot\ln t_1 + n\cdot\ln v_{01},\\ \ln\eta_2 = \ln A + m\cdot\ln t_2 + n\cdot\ln v_{02},\\ \ln\eta_3 = \ln A + m\cdot\ln t_3 + n\cdot\ln v_{03}.\end{cases} \tag{27}$$

Solving the system of equations (27), we determined the value of the coefficient "A"=$3.3\cdot10^4$ and the exponents of "m"=0.54, "n"=2.8, which are constant for this material. Taking dependence (10) as a basis and substituting in it the defined values of "A", "m", "n", we derived a dependence according to which the values of the kinetic coefficient "η" are determined, for crushed cotton stalks:

$$\eta = 3.3\cdot10^{-4}\cdot t^{0.54}\cdot v_0^{2.8}. \tag{28}$$

The coefficients "m" and "n" show the degree of influence of temperature and the rate of filtering of the heating agent on the value of the coefficient "η", so the influence of the filtering speed of the heating agent is more significant. Therefore, the increase in the intensity of the process of the filtration drying of crushed cotton stalks is more influenced by the increase in the rate of filtering of the heating agent than its temperature, which is confirmed by experimental data illustrated in Fig. 2, 3.

Taking into consideration dependence (28) to determine the kinetic coefficient "η" and taking into consideration the value of the kinetic coefficient "a", dependence (11) can be represented as:

$$\frac{w^c}{w_0^c} = 1 - 3.3\cdot10^{-4}\cdot t^{0.54}\cdot v_0^{2.8}\cdot e^{-20.74H}, \tag{29}$$

which makes it possible to predict the intensity of the filtration drying of crushed cotton stalks during the period of full saturation of the heating agent with moisture; it holds until the crushed stalks of cotton reach the critical moisture content w_{cr}^d.

As already noted, the kinetics in the period of partial saturation of the heating agent with moisture is described by equation (12; to use it, the value of the drying speed factor K is necessary. To find this coefficient K, we construct a graphical dependence in the following coordinates

$$\ln\left(\left(w^d - w_e^d\right)/\left(w_{cr}^d - w_e^d\right)\right) = f\left(\tau - \tau_{cr}\right),$$

from which this coefficient is determined as a tangent of the angle of inclination of the straight line to the abscissa axis (Fig. 9–11).

To summarize the kinetics of the filtration drying process during the period of partial saturation of the thermal agent with moisture, it is necessary to calculate the drying rate of the period of complete saturation of the heating agent with moisture N and determine the relative drying coefficient χ.

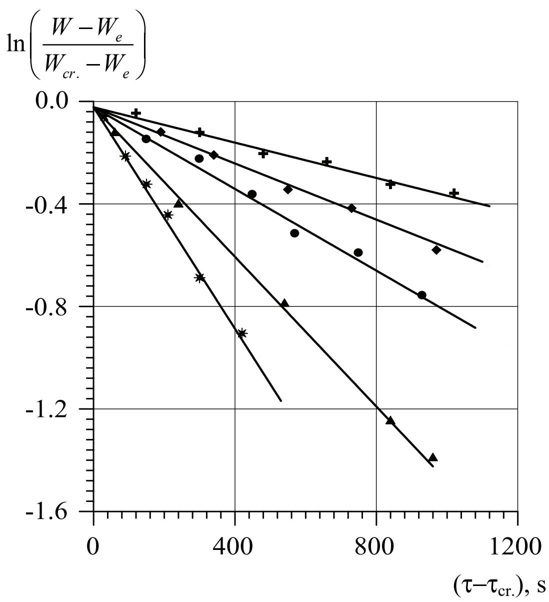

Fig. 9. Determining the coefficient of drying speed during the period of falling rate of moisture removal at different filtration speeds of the heat agent: *H*=100 mm; *t*=60 °C; ✚ – v_0=0.91 m/s; ◆ – v_0=1.25 m/s; ● – v_0=1.71 m/s; ▲ – v_0=1.94 m/s; ✱ – v_0=2.17 m/s

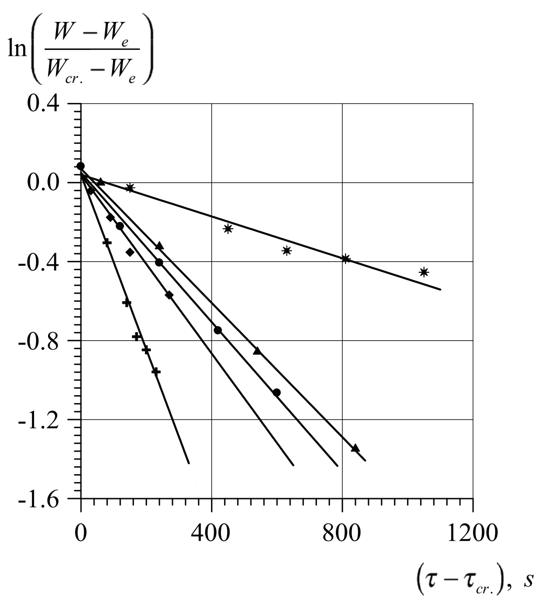

Fig. 10. Determining the coefficient of drying speed during the falling rate of moisture removal at different heights of the stationary layer of crushed cotton stalks: *H*=100 mm; v_0=1.94 m/s; ✚ – *t*=40 °C; ◆ – *t*=50 °C; ● – *t*=60 °C; ▲ – *t*=70 °C; ✱ – *t*=80 °C

The drying speed of crushed cotton stalks in the first period *N* is calculated according to dependence (17) or determined as the tangent of the angle of inclination of that section of the kinetic curve (Fig. 2–4) that corresponds to the period of complete saturation of the heating agent with moisture. Table 3 gives the calculated values of *K* and *N*.

Based on Table 3, we constructed the graphical dependence *K*=*f*(*N*) Fig. 12.

The value of the relative drying factor χ is defined as the tangent of the angle of inclination of the straight line *K*=*f*(*N*) to the axis of abscissa (Fig. 12), which, for crushed cotton stalks, is χ=1.1 kg H_2O/kg dried material.

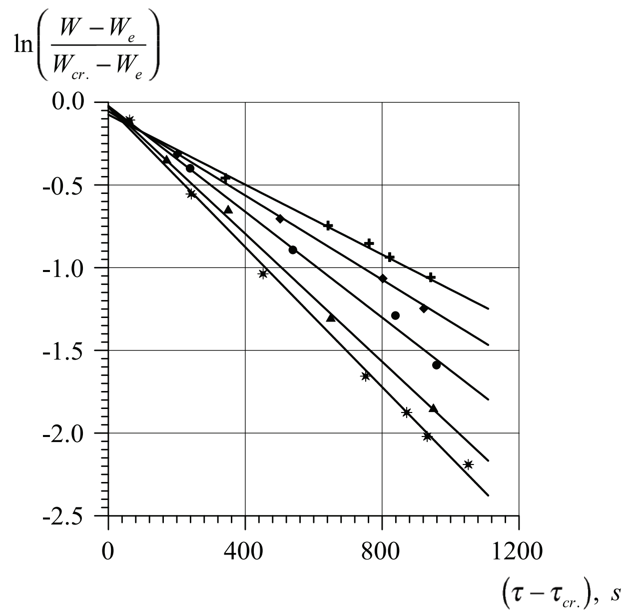

Fig. 11. Determining the coefficient of drying speed during the falling rate of moisture removal at different temperature of the heat agent: *H*=100 mm; v_0=1.94 m/s; ✱ – *t*=40 °C; ◆ – *t*=50 °C; ● – *t*=60 °C; ▲ – *t*=70 °C; ✚ – *t*=80 °C

Table 3

The dependence of *K* and *N* on the parameters of the filtration drying process and the height of the stationary layer of crushed cotton stalks

$N\cdot10^3\,\frac{\text{kg H}_2\text{O}}{(\text{kg dried material}\cdot\text{s})}$	$K\cdot10^3$, 1/s	*t*, °C	*H*, m	v_0, m/s
0.88	0.95	40	0.1	1.94
0.91	0.99	50		
1.18	1.26	60		
1.40	1.59	70		
1.44	1.71	80		
0.22	0.34	60		0.91
0.37	0.55			1.25
0.65	0.80			1.71
1.18	1.25			1.94
1.75	1.82			2.17
0.55	0.56		0.04	1.94
1.25	1.37		0.06	
1.47	1.65		0.08	
1.79	1.99		0.1	
3.46	3.68		0.12	

Taking into consideration the value of χ, dependence (18) can be represented as:

$$w^s=\left(w^s_{cr}-w^s_e\right)\cdot e^{-1,1\cdot N\cdot(\tau-\tau_{cr})}+w^s_e, \quad (30)$$

and dependence (19) – in the form of the following equation:

$$w^s=\left(w^s_{cr}-w^s_e\right)\cdot e^{-1,1\cdot N\cdot\left(\tau-\frac{\left(w^d_0-w^d_{cr}\right)}{N}\right)}+w^d_e. \quad (31)$$

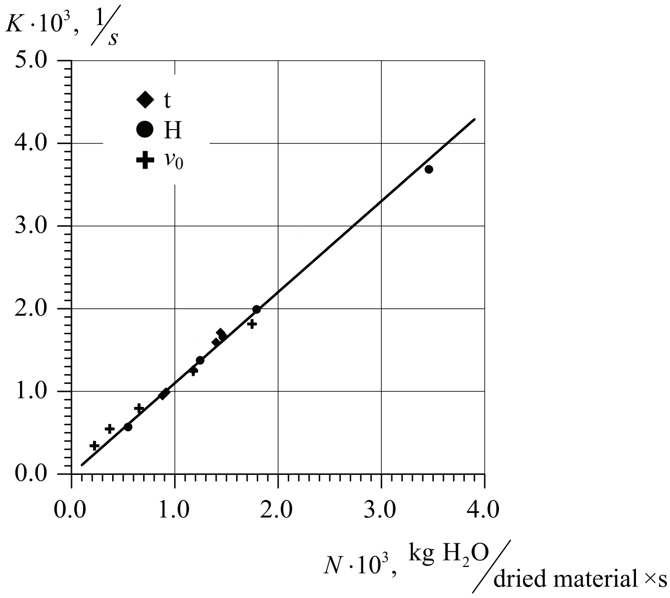

Fig. 12. Dependence of the drying coefficient K on the drying speed N during the period of full saturation of the heating agent with moisture to determine the relative drying factor χ

The resulting dependence (31) makes it possible to summarize the results of experimental studies, namely, to calculate the change in moisture content of the stationary layer of crushed cotton stalks in time until equilibrium moisture content with a heating agent is achieved.

5. 4. Comparing the experimental data with the theoretically calculated data, and establishing the value of relative error

Fig. 13 shows the constructed correlation dependence between the experimental data and those theoretically calculated on the basis of dependences (29) and (31) for all studied temperatures and filtration speeds of the heating agent and the height of the stationary layer H=100 mm.

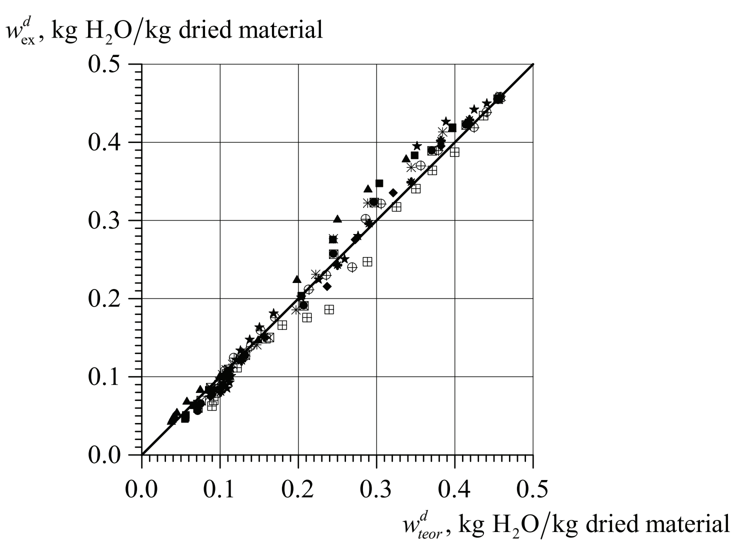

Fig. 13. Correlation dependence between the experimental and theoretically calculated data

Fig. 13 demonstrates that the proposed estimation dependences describe well the process of dehydration of crushed cotton stalks for all the studied temperatures and filtration speeds of the heating agent for the height of the stationary layer H=100 mm. The absolute value of the maximum relative error does not exceed 15.2 %, which is quite acceptable for the design calculations of the filtration drying plant. We accepted as rational, from the point of view of industrial use, the height of the stationary layer of crushed cotton stalks H=100 mm. Taking into consideration the need to ensure high equipment performance and rational costs of both thermal energy and energy to create a pressure drop. An increase in the height of the stationary layer above 100 mm leads to an increase in pressure losses and an increase in drying time and, accordingly, the structural dimensions of the drying plant. Reducing the thickness of the stationary layer of crushed cotton stalks below 100 mm would adversely affect both the productivity of drying equipment and the consumption of thermal energy due to a short period of complete saturation of the heating agent with moisture.

6. Discussion of results of studying the filtration drying of crushed cotton stalks

Fig. 2–4 show that the kinetic curves are similar to classical curves of convective drying and are characterized by the presence of a period of constant drying speed (the first drying period) and periods of decreasing drying speed (the second period). However, since filtration drying is zonal, a straight line on the kinetic curves characterizes the period of full saturation, and the curved line is the period of partial saturation of the thermal agent with moisture.

Analysis of Fig. 2 indicates the reduction of the fictitious filtering speed of the heating agent from 2.17 m/s to 0.91 m/s, that is, by 2.4 times. The drying time of crushed cotton stalks to 0.1 kg H_2O/kg dried material increases from 700 s to 3,000 s, that is, by 4.3 times. This is because an increase in the rate of filtering of the heating agent leads to an increase in the heat and mass transfer coefficients, and, accordingly, the drying process is intensified. Under industrial conditions, high-pressure fans are used to supply the drying agent, and the area of the drying zone would be at least 4 m^2, so it is almost impossible to ensure the speed of the heating agent above 2 m/s. Therefore, the upper limit of the filtering speed of the heating agent was 2.17 m/s.

Analysis of Fig. 3 revealed that an increase in temperature from 40 °C to 80 °C, that is, by 2 times, leads to a reduction in the time of drying of wet crushed cotton stalks to 0.1 kg H_2O/kg dried material from 1,560 s to 420 s, that is, by 3.7 times. This is because crushed cotton stalks contain mainly bound moisture, and an increase in the temperature of the heating agent leads to an increase in molecular diffusion coefficients. At the same time, an increase in the temperature of the heating agent leads to an increase in the heat energy losses with the spent heat agent and the dried material that is unloaded from the drying plant. There are also losses of thermal energy to the environment from the surface of the drying plant casing, which requires an increase in the thickness of the insulating layer and leads to an increase in the capital costs for its manufacture. Therefore, the chosen upper-temperature limit of the heating agent is 80 °C.

Analysis of Fig. 4 indicates that an increase in the height of the stationary layer of crushed cotton stalks by 3 times leads to an increase in drying time by 12.5 times. Given that filtration drying is zonal in nature, the increase in the height of the stationary layer leads to an increase in the time of movement of the heat and mass exchange zone. The heating agent, filtering through a stationary layer of material, gives part of the heat to already dried cotton stalk particles, so the temperature of the heating agent decreases in height of the layer, and the drying time increases with the height of the layer. In addition, the upper layers of the material, with the growth of the total height of the layer, are heated to higher temperatures because they are in much longer contact with the heating agent, which leads to unproductive energy costs. Therefore, the chosen upper height limit of the stationary layer of crushed cotton stalks is 120 mm.

A feature of the proposed method is that filtration drying belongs to high-intensity methods of drying wet materials and because the heating agent is filtered through a layer of dispersed material. At the same time, the contact area of the heating agent with wet material, the coefficients of heat and mass exchange, and the degrees of saturation of the heating agent with moisture are much larger than those with convective drying or in the boiling layer. Therefore, for drying wet materials during filtration drying, a much lower temperature of the heating agent is used than during convective drying, which has a positive effect on both energy costs and the quality of the finished product.

The estimation dependences are valid only within the limits of changing the filtering speed of the thermal agent of 0.91–2.17 m/s, the temperature of the heating agent of 40–80 °C, and the heights of the stationary layer of 40–120 mm.

Our results of studying the kinetics of the filtration drying of crushed cotton stalks relate to the equipment involved in the experimental studies. These results do not take into consideration the loss of heat into the environment, as well as the cost of heat for heating transport mechanisms and other technological equipment. The derived estimation dependences of the drying coefficient K on drying speed N during the period of full saturation of the heating agent with moisture should be used for design calculations of drying equipment. However, during the commissioning of the designed drying equipment, it will no doubt be necessary to conduct additional experimental research to optimize the process of drying crushed cotton stalks.

To design equipment for the implementation of the process of the filtration drying of crushed cotton stalks, dependences are necessary that would be convenient to use to calculate the drying time.

The critical drying time τ_{cr} can be determined by using graphic dependences (Fig. 5–7) or by calculations based on dependence (21):

$$\tau_I = \frac{\left(w^d - w^d_{cr}\right)}{w^d_0 \cdot 3.3 \cdot 10^{-4} \cdot t^{0.54} \cdot v_0^{2.8} \cdot \tau \cdot e^{-20.74 \cdot H}}, \qquad (32)$$

and drying time during the period of partial saturation of the heating agent with moisture – according to dependence (22):

$$\tau_{II} = \frac{1}{\chi \cdot N} \cdot \left(1 + \ln \chi \left(w^c - w^c_k\right)\right) =$$
$$= \frac{1}{\left(1{,}1 \cdot w^c_0 \cdot 3.3 \cdot 10^{-4} \cdot t^{0.54} \cdot v_0^{2.8} \cdot \tau \cdot e^{-20.74 \cdot H}\right)} \times$$
$$\times \left(1 + \ln\left(1.1 \cdot N \cdot \left(w^c - w^c_k\right)\right)\right). \qquad (33)$$

The total time of the filtration drying of crushed cotton stalks from the initial moisture content of the leaves to the final one can be calculated as the sum of dependences (32), (33).

Given that the moisture in the crushed cotton stalks is bound and evaporates from the inner layers of the particle to the surface by molecular diffusion, it would be advisable to determine the coefficient of diffusion of moisture depending on the temperature of the heating agent. Determining the coefficient of internal diffusion during filtration drying would make it possible to more accurately choose the rational parameters of the heating agent both in terms of its temperature and its flow rate.

7. Conclusions

1. We have theoretically analyzed the kinetics of drying wet materials. The experimental studies into the kinetics of the filtration drying of crushed cotton stalks have been generalized. The resulting dependence is $\frac{w^c}{w^c_0} = 1 - 3.3 \cdot 10^{-4} \cdot t^{0.54} \cdot v_0^{2.8} \cdot e^{-20.74 \cdot H}$, which makes it possible to generalize the kinetics of the filtration drying of crushed cotton stalks during the period of complete saturation of the heat agent with moisture within the limits of changing the moisture content of crushed cotton stalks.

2. We have experimentally investigated the kinetics of the filtration drying of crushed cotton stalks at different temperatures and filtration speeds of the heating agent, as well as at different heights of the stationary layer. The results of the experimental studies show that the process occurs during periods of full and partial saturation of the heating agent with moisture.

3. The derived dependences $w^d = \left(w^d_{cr} - w^d_e\right) \cdot e^{-1.1 \cdot N \cdot (\tau - \tau_{cr})} + w^d_e$ and $w^d = \left(w^d_{cr} - w^d_e\right) \cdot e^{-1.1 \cdot N \cdot \left(\tau - \frac{\left(w^d_0 - w^d_{cr}\right)}{N}\right)} + w^d_e$, make it possible to calculate a change in the moisture content of crushed cotton stalks in time during the period of partial saturation of the heating agent with moisture until the crushed stalks of the cotton reach the moisture content in equilibrium with the thermal agent.

4. The comparison of the experimental data with those theoretically calculated on the basis of our dependences has shown that the maximum absolute value of relative error does not exceed 15.2 %.

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