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Substantiation of modes of drying alfalfa pulp by active ventilation in a laboratory electric dryer

Abstract. *The article presents theoretical and experimental studies to determine the rational modes of the drying process of alfalfa pulp. Theoretical research was based on the basic laws of drying of capillary – porous bodies which include alfalfa pulp. Experimental studies were conducted in a laboratory installation, which recorded the main mode parameters of the process, such as temperature, relative humidity and consumption of the drying agent (air), the specific gravity of the load layer of the material, its current moisture content. The obtained dependences of the total duration of the process can be used in the design of plants for drying pulp from alfalfa and other similar materials.*

Streszczenie. *W artykule przedstawiono badania teoretyczne i eksperymentalne mające na celu określenie racjonalnych trybów procesu suszenia miazgi lucerny. Badania teoretyczne oparto na podstawowych prawach suszenia kapilar – ciał porowatych zawierających miazgę lucerny. Badania eksperymentalne przeprowadzono na instalacji laboratoryjnej, w której rejestrowano główne parametry modowe procesu, takie jak temperatura, wilgotność względna i zużycie środka suszącego (powietrza), ciężar właściwy warstwy obciążonej materiału, jego aktualna wilgotność . Otrzymane zależności całkowitego czasu trwania procesu można wykorzystać w projektowaniu instalacji do suszenia pulpy z lucerny i innych podobnych materiałów.* (***Analiza sposobów suszenia miazgi lucerny przez aktywną wentylację w laboratoryjnej suszarce elektrycznej***)

Keywords: periods of drying, process parameters, specific load of pulp material, warm air.
Słowa kluczowe: suszenie miazgi lucerny, gorące powietrze.

Introduction

The number of vegetarians on the Earth is gradually increasing. But not so fast that humanity could do without livestock products. For example, in Ukraine the vegetarians are now accounted for just over 5%. Thus, the production of animal products is an important problem that cannot be solved without advanced feed production. After all, due to the shortage of quality feed, 4 million tons of milk and almost 0.2 million tons of meat are under produced annually in Ukraine [1, 2]. It should be noted that now the most important task is to provide quality feed, such feed that has a high coefficient of digestibility.

Traditional types of feed (hay, haylage, silage, etc.) can not provide the required level of digestibility, especially for new highly productive breeds of animals [3]. This problem can be solved by supplementing the traditional diet with new high-energy feeds [4].

Analysis of literary sources and problem statement

The digestibility of feed nutrients is affected by the ratio in the diet between digestible protein and without nitrogenous substances [5]. A rational combination of amino acid composition and high energy value can be achieved by fractional processing of green mass of alfalfa, which helps to obtain two main components: protein-vitamin paste and pulp [6]. The authors have already focused in [7] on the technology of fractional processing of alfalfa and the nutritional qualities of the feed, so let's move on to the question of drying one of the fractions, namely the one that comes out after squeezing the crushed plant mass. Why is the drying of the pulp? For efficient use of feed fractions, they need to be accumulated, stored, and therefore somehow preserved. The most common way of preserving feed is their drying, so the process of bringing the moisture content of the material to a level at which it can be stored for a long time without damage of its quality [8].

However, the loss of nutrients, and also the quality of feed, energy consumption for the drying process depend on the method and mode parameters of the process, which must be scientifically justified for specific production conditions. One of the effective and widespread methods of drying similar materials is active ventilation with atmospheric or heated air of a fixed dense layer of material. Knowledge of the laws of the drying process in a dense layer will allow you to control this complex process, to identify ways to make fuller use of the drying potential of air, to determine the rational flow of air blown through the layer of material.

General theoretical issues of transformation of heat and substance during the drying process are solved for bodies of classical form. But in the real case it is necessary to simplify this process a little and to accept certain assumptions [8, 9].

For example, in [10] the process of drying leaf-stem materials is studied only from the point of view of mass exchange processes, in [11] the internal heat source is taken into account, which is in a thick layer, in [12] it is developed an analytical mathematical model of heating and drying processes of plant materials in thick stationary layer whose density varies in height. In [13] the issue of modeling of drying modes of dispersed materials in real dryers of column type is considered. These and many other theoretical studies are implemented in real machines, units for processing and storage of crop products [14, 15].

Purpose and tasks of research

The aim of the research is to increase the efficiency of use of alfalfa feed by determining the rational parameters of the drying process of one of the components of fractional processing – alfalfa pulp.

But despite such a wide range of theoretical and experimental studies, as we have already indicated, in each case it is necessary to conduct research to substantiate the method and determine the rational parameters of the drying process of vegetable raw materials. So, such studies on the drying of alfalfa processed products are relevant.

Improving the efficiency of the drying process of products of fractional processing of alfalfa by obtaining analytical dependences for the analysis of the drying process with their subsequent use, to justify the operating parameters of the real drying equipment.

Materials and methods

Most wet plant materials and their components, including pulp from green alfalfa plants, belong to capillary-porous bodies. The drying curves of these bodies have two distinct periods: constant and falling velocities.

The equation of the drying speed curve in the first period has the form [16, 17, 18]:

(1) $$-\frac{dw}{d\tau} = N = const\ ,$$

where $\frac{dw}{d\tau}$ – drying speed $\frac{kg_{moist}}{kg_{\text{a,c,p}} \cdot hours}$; *N* – drying speed in the first period; τ– time, hours.

Analysis of the results of experimental studies shows that to describe the drying process of alfalfa pulp in the second period, you can use the equation [16, 17]:

(2) $$\frac{dw}{d\tau}/N = \Psi = \frac{(W - W_p)^m}{A + \beta\,(W - W_p)^m}\ ,$$

where *Ψ* – common drying speed; *W*, W_p – current and equilibrium moisture content of the material, $\frac{kg_{moist.}}{kg_{\text{a,c,p}}}$.

We have already written about the equilibrium moisture content of products of fractional processing of alfalfa in [6]. The exponent of degree m characterizes the relationship of moisture with the material or the index of internal diffusion of moisture and does not depend on the parameters of the layer and the moisture content of the material.

Dimensionless coefficients *A* and *β* depend on the parameters of the material layer (mainly on its thickness).

The time during which the average moisture content of the material layer decreases from the initial *W*_0 to the final *W*_2 value, consists of the duration of drying in the first *τ*_1 and the second *τ*_2 periods:

(3) $$\tau = \tau_1 + \tau_2 .$$

Let's integrate equation (1) in the range from *W*_0 to *W*_ *(cr)*, and equation (2) from *W_cr* to *W*_ (2), and as a result we obtain expressions to determine the drying time of alfalfa pulp, respectively, in the first and second periods:

(4) $$\tau_1 = \frac{W_0 - W_{cr}}{N}\ ,$$

(5) $$\tau = \frac{1}{N}\left[A \int_{W_2}^{Wcr} \frac{dw}{(w - w_p)^m} + \beta(W_{cr} - W_2)\right],$$

where W_{cr} – the average critical moisture content of the material layer, kg / kg, so the moisture content at which the first drying period passes into the second.

After substituting in equation (3) the values of *τ*_1 and *τ*_2 from (4) and (5), as well as taking into account that for capillary-porous bodies, which include alfalfa pulp, the exponent *m* = 1 [17], we obtain the equation to determine the total drying time of the pulp layer:

(6) $$\tau = \frac{1}{N}\left[\, W_0 - W_{cr} + \mathrm{A}\, ln \frac{W_{\text{кр}} - W_p}{W_2 - W_p} + \beta\ (W_{cr} - W_2)\right].$$

In equation (6), the coefficients *A* and *β*, the values of critical and equilibrium moisture content are determined experimentally.

The drying speed of the material in the first period *N* depends on the parameters of the layer (height, its density) and the coolant (temperature, humidity, speed and flow rate) [18, 19].

As a result of analytical researches the criterion equation by means of which it is possible to define *N* was received:

(7) $$N_{u_v} = B\left(\frac{v\rho_n l}{\mu g}\right)^{K_1} \left(\frac{H}{l}\right)^{K_2},$$

where *υ* – air speed and free section; ρ_n – air density; *l* – the determining size of the particles (uses, as a rule, the weighted average particle length); *μ* – dynamic air viscosity; *H* – layer height; B^{k1}, B^{k2}– constants that are determined experimentally.

In equation (7) N_{u_v} is a modified Nusselt criterion for the volumetric heat transfer coefficient. Its value can be determined from the following equation [17]:

(8) $$N_{u_v} = \frac{\rho_o l^2}{\lambda_n} \cdot \frac{N}{\Delta P},$$

where ρ_o – the density of the particles therefore in their natural structural state; λ_n – coefficient of mass conductivity of the air; ΔP – average difference in partial vapor pressure near the surface of the particles and in the air.

From equations (7) and (8) we can obtain an expression for determining the drying speed in the first period:

(9) $$N = B\,\frac{\lambda_n\,\Delta P}{\rho_o\, l^2} \cdot \left(\frac{V\rho_n\, l}{\mu g}\right)^{K_1} \cdot \left(\frac{H}{l}\right)^{K_2},$$

The average difference of partial pressures Δ*P* in equation (9) can be expressed through the initial drying potential which is characterized by the difference between the moisture content of adiabatically saturated air and that entering the layer; the height of the layer *H* – due to the specific load of the material per unit plane of the grid on which it is located; air velocity on the free section *V* – due to the specific air flow rate *G_n*, so

(10) $$\Delta P = z_1(\, d_{\text{н}} - d_1\,) = z_1 \Delta d_1;\ \ \mathrm{H} = z_2 \cdot \rho;\, V\rho_n = z_3 G_n \rho_n,$$

where z, z, z_3 – coefficient of proportionality.

After some transformations, equation (9) gets:

(11) $$N = (\, G_n \rho_n\,)^k P^{k_2} \Delta d_1 \left[\frac{B\, z_1\, z_2^{k^2}\ z_3^{k^1} \lambda_n}{\mu \cdot g \cdot p_0 \cdot l^{2-k_1}}\right].$$

After substituting the value of *N* from equation (6) from equation (11), we obtain the equation for determining the total duration of drying of the pulp layer:

(12) $$\tau = \frac{W_0 - W_{cr} + Al_n \frac{W_{cr} - W_0}{W_2 - W_p} + \beta\,(\,W_{cr} - W_2\,)}{G_n {\rho_n}^{K_1} P^{K_2} \Delta d_1 \left[\frac{B\, z_1\, z_2^{k^2}\ z_3^{k^1} \lambda_n}{\mu \cdot g \cdot \rho_0 \cdot l^{2-K_1}}\right]}.$$

This analytical dependence determines the total drying time from a number of parameters, including initial, critical, equilibrium and final moisture content, specific flow rate of air blown through the material layer, specific load of the material layer, temperature and humidity, physical and chemical properties of the material *m* = 1, *A* and *β*.

The initial moisture content is determined by the degree of mechanical extraction of green plants. This moisture content, as well as the final, are set by the conditions of the technological process. The initial drying potential of air is determined by the *I-d* diagram, based on the average values of its temperature and humidity. The values of the exponents *k*_1 and *k*_2, as well as the coefficients *A*, *β*, *B*, *z*_1, *z*, *z*_3 are determined experimentally.

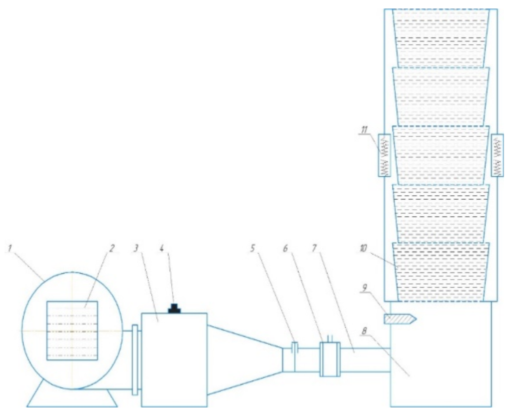


Fig. 1. The scheme of laboratory installation: 1 – the fan; 2 – electric heater; 3 – distribution chamber; 4 – temperature regulator; 5 – valve; 6 – diaphragm; 7 – air duct; 8 – mixing chamber; 9 – temperature sensor; 10 – loading container; 11 – device for sealing containers.

Experimental studies of the drying process of alfalfa pulp in a thick layer were performed on a laboratory installation, the scheme of which is shown in (Fig. 1).

The main elements of the laboratory installation are the fan 1 Ts 4–70 № 8, electric heater 2 PNE-67.5, distribution chamber 3, air duct 7, containers with mass 10, shut-off, regulating and measuring equipment. The air flow was monitored by means of a diaphragm 6 mounted on a straight section of the air duct 7. In the mixing chamber 8 is installed a thermometer 9 to monitor the air temperature at the inlet to the drying chamber. In the chamber are placed 5-10 (depending on the required height of the layer of container material) 10 for samples of the test material. They have the shape of a truncated quadrangular pyramid with an angle of inclination of the side surface of 5°, a height of 0.2 *m* and an area of the lower base of 0.1 m^2.

The bottom of each container is made of the net of mesh with 1.5 × 1.5 *mm* meshes, around the perimeter of which is glued with soft rubber. Sealing between the containers is provided by a tensioning device 11, and the side walls of the containers are insulated.

To automatically control the temperature of the drying agent (air) is used a sensor 4 [20, 21] installed in the distribution chamber 3. The laboratory unit has three drying columns for the experiment in three replications [22]. The air velocity in the working part of the channel was measured using a diaphragm and a traction meter. Simultaneously, psychrometric thermometers with a separation price of 0.2 degrees measured the air temperature at the entrance to the material layer.

The moisture content of the material during drying was determined by periodic weighing of containers with samples on laboratory scales TVE-12-05 [23]. The initial and final moisture content of the material was determined according to the standard method of DSTU 29144:2009 [24].

The mode parameters of the material (alfalfa pulp) and drying agent (air) during the experiments were as follows: the average initial temperature of the drying agent varied sequentially with an interval of 10 degrees from 297 to 327 *K*, specific air flow – at intervals of 200-300 m^3 / ($h \cdot m^2$) from 340 to 1600 m^3 / ($h \cdot m^2$), and the specific load of the material layer varied from 7 to 100 *kg* / m^2.

Research results

Analysis of a large number of curves obtained at different modes allowed to determine the individual dependences of the drying rate in the first period and the total drying time of the alfalfa pulp layer on the initial drying potential (Fig. 2), specific air flow, specific layer load.

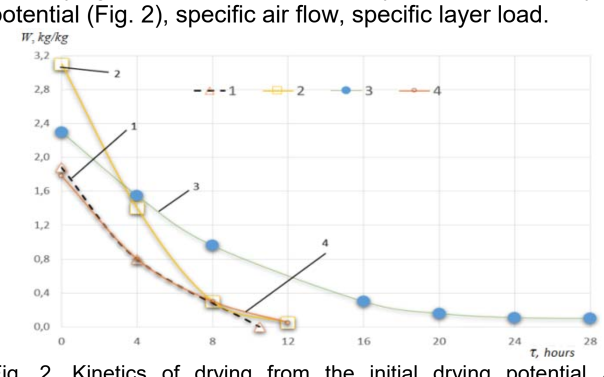


Fig. 2. Kinetics of drying from the initial drying potential *Δd (g.moist./kg.sp.)* at *Psh* = 21.0 *kg* / m^2; G_n = 500 m^3 / *year*: 1 – 10.2; 2 – 4.5; 3 – 6.7; 4 – 10.0.

It is established that the drying rate of the layer in the first period is directly proportional to the initial drying potential of air: *N* ~ Δ*d*, which agrees with equation (11). With an increase in the specific flow of air that is blown through the layer of material, there is a significant decrease in the duration of drying (Fig. 3).

If we construct the dependence of N from $G_n \rho_n$, in logarithmic coordinates, we obtain a straight line whose tangent of the angle of inclination to the abscissa axis is equal to the exponent K_1 of equations (11) and (12). Within the range of G_n from 340 to 1300 m^3/h $K_1 = 0.65$, so $N \sim \rho_n G_n^{0,65}$. When analyzing the effect of the specific load of the alfalfa pulp layer on the drying speed and duration of the process, it was found that the slope of the drying curves decreases with increasing specific load (Fig. 4). The average drying speed decreases sharply (Fig. 5).

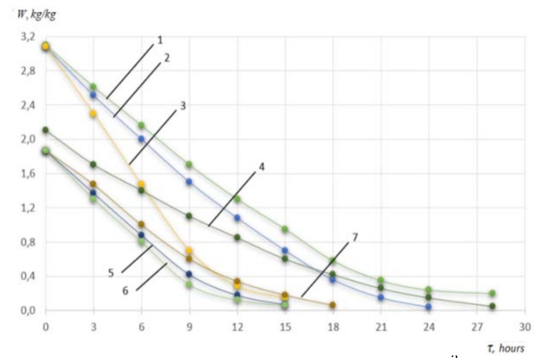


Fig. 3. Drying kinetics from proportion air flow *Gn* (m^3 / *h*) at *Psh* = 44.2 *kg* / m^2 ; *Δd* = 10 gr_{moist} / *kg.sp*.: 1 – 500; 2 – 560; 3 – 1115; 4 – 340; 5 – 875; 6 – 910; 7 – 480.

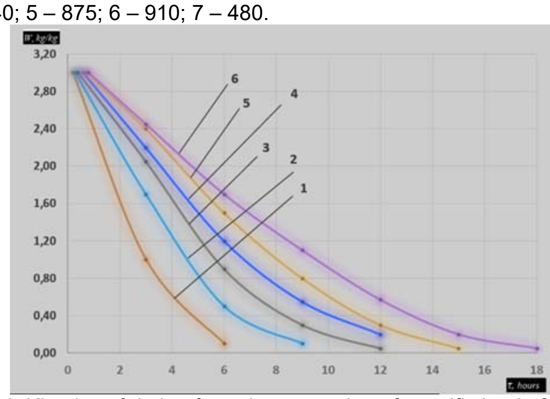


Fig. 4. Kinetics of drying from the proportion of specific load of the material P_{sh} (*kg* / m^2) at Δ*d* = 10,1 $gr_{moistr.}/kg_{s.p.}$, G_n = 500 m^3 / *h*: 1 – 13.8; 2 – 21.6; 3 – 28.9; 4 – 36.1; 5 – 43.5; 6 – 50.5.

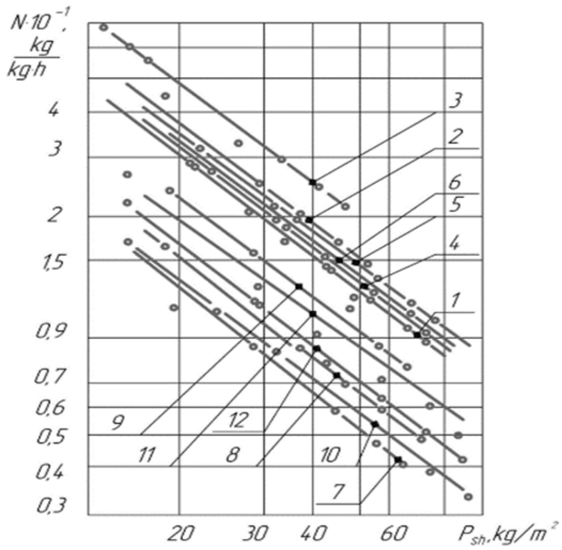


Fig. 5. The dependence of the drying rate of the material in the first period from the proportion of the specific load (experimental conditions are given in table. 1).

From fig. 5 it is shown that regardless of the drying mode, the dependence of *N* from *P* are parallel lines. The tangent of the angle of inclination of these lines to the abscissa is numerically equal to the exponent K_2 of equations (11) and (12) and is - 0.972, so it is approaching to - 1. The multiplier in square brackets in these equations when changing the mode parameters of the layer and air remains constant and is equal to 0.0107.

Table 1. Conditions for conducting experiments.

№	Mode parameters of the material layer and air					
	t_1, K	$\varphi, \%$	$Gp, m^3 / h$	$\Delta d,\ g_{moist} / kg_{s.p.}$	$W_0, {}^{kg}/_{kg}$	K_2
1	320.8	11.0	500	9.35	3.10	0.96
2	326.6	7.5	560	10.90	3.10	0.92
3	324.2	9.0	1115	10.40	3.10	0.98
4	333.7	15.0	1060	7.60	1.88	0.99
5	315.1	14.0	1000	8.30	1.88	0.99
6	312.9	16.0	1040	7.50	1.88	0.97
7	302.1	38.0	340	4.00	2.28	0.95
8	303.3	35.0	480	4.40	2.28	0.93
9	303.5	35.5	980	4.60	2.28	0.95
10	297.4	45.0	560	2.80	1.62	0.94
11	298.9	44.0	972	3.40	1.62	0.98
12	304.0	32.5	1094	3.31	1.62	0.86

Thus, the processing of experimental data allowed to obtain the following equation to determine the drying rate of the layer in the first period.

(13) $$N = \frac{0.0107}{Psh}\,\Delta d_1 (G_n\ \rho_n)^{0.65}.$$

For further research, we will make some transformations in equation (5): let's take the integral, and then multiply both parts of the equation by $N / (W_{cr} - W_2)$ and for *m* = 1 we obtain:

(14) $$\frac{N\tau_2}{W_{cr} - W_2} = \frac{A}{W_{cr} - W_2}\, ln\, \frac{W_{cr} - W_P}{W_2 - W_P} + \beta.$$

To determine the coefficients *A* and *β* we have built by experimental curves of drying time for different values W_2 the dependence of the value $N\tau_2/(W_{cr} - W_2)$ as a function from:

$$\left(\frac{1}{W_{cr} - W_2} \cdot ln \cdot \frac{W_{cr} - W_p}{W_2 - W_p}\right) \text{ when } P_{sh} = \text{const}.$$

The result is a straight line which on the *y*-axis cuts a segment equal to *β*, and the tangent of the angle of inclination of this line to the abscissa determines the coefficient *A*.

It is established that the value of the coefficients *A* and *β* is influenced by the specific load of the material. The dependence of these coefficients on the value of P_{sh} is shown in (Fig. 6).

Presented in Fig. 6 (a, b) dependences can be described by empirical dependencies:

(15) $$A = 13.25 \cdot P_{sh}^{-1}.$$

(16) $$\beta = 0.24\, (P_{sh} - 10)^{0.3}.$$

The results of processing of experimental data allow to obtain analytical dependences to determine the main operating parameters of the drying process of alfalfa pulp in a thick layer. For example, the required specific air flow rate can be determined from the following dependence:

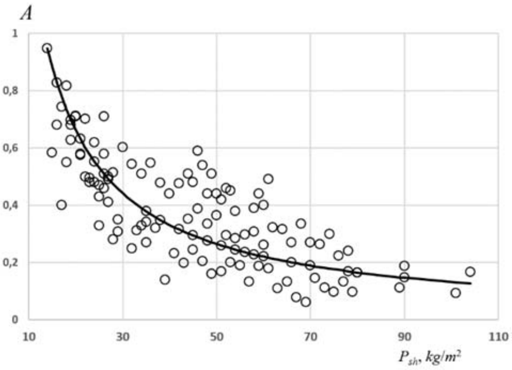
(17) $$G_n = \left\{\frac{[W_0 - W_{cr} + ln\frac{W_{cr} - W_p}{W_2 - W_p} + \beta\,(W_{cr} - W_2\,]\cdot P_{sh}}{0.0107\ \rho_n^{\,0.65}\,\Delta d_1 \cdot \tau}\right\}^{1.54}.$$

Similarly, you can get the dependences to determine the drying time in the first and second period for any current moisture content *W*:

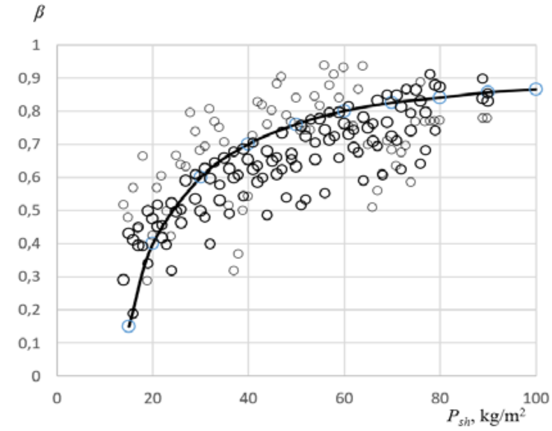
(18) $$\tau_1 = \frac{P_{sh}\,(W_0 - W_{cr})}{0.0107\,(\rho_n \cdot G_n)^{0.65}\,\Delta d_1}.$$

(19) $$\tau_2 = \frac{[\,13.5\ ln\,\frac{W_0 - W_p}{W - W_p} + 0.24\,P_{sh}\,(P_{sh} - 10)^{0.3}\,(W_0 - W)}{0.0107\,(\rho_n\,G_n)^{0.65}\,\Delta d_1}.$$

From equations (18) and (19) it follows that the duration of the drying process of the alfalfa pulp layer in the first period does not depend on the properties of the material, but is a function of temperature, humidity and specific air flow, as well as specific load per unit area of the dryer. In the second period, the duration of the drying process, in addition to these factors, depends on the properties of the material, which is taken into account by the coefficients *m*, *A*, *β*.



a)



b)

Fig. 6. Dependence of dimensionless coefficients *A* (a) and *β* (b) on the specific load of the material.

To verify the obtained analytical dependences, the calculated data on the drying time of the pulp layer were compared with experimental ones. The experimental conditions are given in table 1. It is established that the deviation of the experimental and calculated values of the drying time is within ± 9%, which is an acceptable result for such processes.

Thus, according to the known temperature and humidity, the average initial moisture content of the material, the specific load of the material layer per unit area of the dryer, the drying time, you can use dependence (17) to determine the rational flow of air blown through the layer. So you can choose a rational equipment (fan) when designing plants for drying pulp.

Equilibrium W_P and critical W_{cr} moisture content are also present in the analytical dependences. The authors have already written about the equilibrium moisture content and methods of its determination [5]. The critical moisture content of the material can be determined from the expression for the consolidated drying rate *Ψ*, which at *W* = W_{cr} is equal to one. From equation (2) taking into account (15) and (16) we obtain:

(20) $$W_{cr} = \frac{13.25}{P_{sh} - 0.24\, P_{sh}(Psh-10)^{0.3}} + W_P.$$

As you can see, the critical moisture content (so the moisture content at which the first drying period ends and the second begins) does not depend on the properties of the material, as mentioned above (formula 18).

Conclusions

Duration of drying in the first period of alfalfa pulp in the thick layer does not depend on the properties of the material, but only from the parameters of the layer and air that blows it.

We have obtained the dependences for determining the rational parameters of the drying process of alfalfa pulp. These dependences can be used to select the equipment of the dryer for drying alfalfa pulp.

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