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O.S. Ivashchuk, V.M. Atamanyuk, R.A. Chyzhovych, S.A. Barabakh

KINETIC REGULARITIES OF FILTRATION DRYING OF CORN ALCOHOL DISTILLERY STILLAGE

Lviv Polytechnic National University, Lviv, Ukraine

We studied the kinetic regularities of filtration drying of corn alcohol distillery stillage. The kinetic curves characterizing the process of filtration drying of corn alcohol distillery stillage at different parameters of the stationary layer of the studied material and thermal agent were obtained: at different heights of the wet material, and at different temperatures of the thermal agent and the velocity of its movement through the stationary layer. The calculated dependences for determining the intensity of the filtration drying process in two conditional drying periods were proposed. The equations for the calculation of drying time separately for each conditional drying period were given. The maximum value of the relative error is 19.42%, while the average relative error is 5.37%, which is an acceptable deviation in practical calculations of experimental and industrial drying installations.

Keywords: drying, filtration drying, alcohol distillery stillage, kinetics, kinetic curve, drying period, stationary layer.

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Introduction

Alcohol distillery stillage is the main by-product remaining after distillation from mash at industrial ethanol production facilities [1]. Depending on the production technology used at a particular production facility, 10 to 15 liters of alcohol distillery stillage are produced per liter of ethanol [2]. Global production of alcohol is constantly growing, as it is used in various industries, including chemical, food, pharmaceutical, etc. [3].

Taking into account the large volumes of alcohol distillery stillage formation [4], there is a need to reuse the by-product, which at the same time will improve the ecological situation by reducing the negative impact on the environment.

The alcohol distillery stillage can be used as a food product for animals [5], as a fertilizer for agricultural land [6], for biogas production [7], and for the production of alternative solid fuels [8].

Due to the high moisture content of alcohol distillery stillage (about 75–80%), its shelf life is reduced to several days, which greatly complicates its reuse, storage, and transportation [1]. This problem can be solved by drying the plant material to moisture values that are optimal for long-term storage and secondary use [9,10].

In this paper, it is proposed to use the filtration drying method, which has a number of advantages [11,12] over others for drying plant dispersed materials with a high moisture content. The moisture content of a dispersed material decreases when a thermal agent passes through its stationary layer under the influence of a pressure difference [1]. It should be noted that optimization of the drying process has great potential to reduce energy consumption and improve the results of this important technological process [13].

The study of filtration drying kinetics of wet materials is an important step in establishing the parameters that characterize the course of this process, its duration, and optimal conditions. In general, the drying kinetics is determined by the structural features of the material, the mechanisms of heat and mass transfer that occur within the material and between its surface and the environment. The nature of the kinetic curves may vary depending on the properties of the material to be dried, such as moisture content, the form of moisture bonding with the material, etc., as well as the parameters of the thermal agent, such as moisture content, temperature and velocity.

Experimental

To study the kinetics of the filtration drying process, corn alcohol distillery stillage was used (Fig. 1) obtained at the production line of the SE «Vuzlove distillery» (Vuzlove, Lviv region, Ukraine) [8].

Fig. 1. Dried corn alcohol distillery stillage

To carry out experimental studies of the filtration drying process, an experimental laboratory installation was used [1], which provides the ability to conduct comprehensive studies of drying wet material by changing the parameters of the drying process: the height of the material layer H, the temperature of the thermal agent T, and the velocity of the thermal agent ν_0.

The initial material, with an initial moisture content determined according to the methodology [1], was dried in a cylindrical container [14] of the experimental laboratory installation. The height of the test material layer was adjusted using the value of the bulk density of the wet material, the method of determining which is described elsewhere [1].

Three series of experiments were conducted to study the kinetics of the filtration drying process of corn alcohol distillery stillage. In each series, certain process parameters were varied, namely, the temperature of the thermal agent, the velocity of the thermal agent, and the height of wet material layer.

According to the theory [11,15], the drying process can be divided into two conditional periods, the first of which is characterized by complete saturation of the thermal agent with moisture, while the second period is characterized by partial saturation of the thermal agent with moisture. Furthermore, it was proposed to establish calculation dependences that characterize the drying process of a dispersed material in the conditional first (1) and second (2) drying periods:

$$w^c = w^c_0 (1 - A \cdot T^m \cdot \nu_0^n \cdot \tau \cdot e^{-aH}), \quad (1)$$

$$w^c = (w^c_{cr} - w^c_e) \cdot e^{-\chi \cdot N \cdot (\tau - \tau cr)} + w^c_e, \quad (2)$$

where w^c is the running value of the moisture content of the material, kg H_2O / kg dry material; w^c_0 is the initial value of the material moisture content, kg H_2O / kg dry material; A, m, n are the equation coefficients that are constant for a certain material; T is the temperature of the thermal agent, ^{0}C; ν_0 is the velocity of the thermal agent, m/s; τ is the drying time, s; a is the kinetic coefficient; H is the height of the wet material layer, m; w^c_{cr} is the critical moisture content of wet material, kg H_2O / kg dry material; w^c_e is the equilibrium value of the moisture content of the material, kg H_2O / kg dry material; χ is the relative drying coefficient, kg H_2O / kg dry material; N is the drying rate during the period of complete saturation of the thermal agent with moisture, kg H_2O/(kg dry material·s); and τ_{cr} is the critical drying time, s.

The kinetic equations for the filtration drying may be used to predict and optimize the process, determine optimal parameters, develop drying equipment, etc.

Results and discussion

The study of changes in the dispersed material moisture content during filtration drying was carried out for the corn alcohol distillery stillage, the bulk density of which is 407.5 kg/m^3 and the initial moisture content is 72.78 wt.%. During the research, the following parameters of the stationary material layer were changed: the height of the wet material H (40 mm, 80 mm, 120 mm, and 160 mm), as well as the parameters of the thermal agent flow, including its temperature T (60^{0}C, 70^{0}C, 80^{0}C, and 90^{0}C) and the velocity ν_0 (1.24 m/s, 1.76 m/s, 2.29 m/s, and 2.82 m/s) through the stationary layer of the studied material. In the case of a change in one of the three parameters H, T, ν_0, the others remained unchanged. For each variable parameter, the average value was chosen for comparison as follows: H=120 mm, T=70^{0}C, and ν_0=1.76 m/s. The obtained experimental data are presented in the form of graphical dependences of the change in the moisture content of the test material w_c over time τ (Figs. 2–4).

Analyzing the graphical dependence shown in Fig. 2, an increase in the drying time is observed, along with an increase in the height of the layer of the studied wet material. At H=160 mm, the final moisture content of the material is reached in about 3800 s, while at H=40 mm it is reached in only 1200 s. Thus, there is a decrease in drying time by ~3.2 times, with a decrease in the height of the layer of the experimental material.

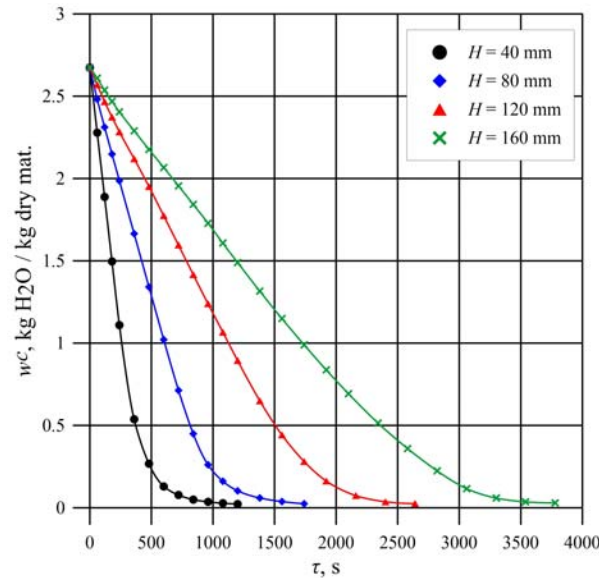

Fig. 2. Changes in the moisture content of the corn alcohol distillery stillage over time depending on different heights of wet material (at T=70⁰C, and v_0=1.76 m/s)

The drying kinetic curves shown in Fig. 3 for the alcohol distillery stillage shows the change in the time to reach the final moisture content depending on the temperature of the drying agent. As the temperature increases (from 60⁰C to 90⁰C), the time required for drying decreases from ~3300 s to ~2200 s.

As a result of studies of the effect of the thermal agent velocity, a reduction in the drying time of wet material is observed with an increase in the velocity of the thermal agent (Fig. 4).

The results of a series of experiments of the drying process, shown in Figs. 2–4, clearly indicate the effectiveness of changing the temperature of the thermal agent compared to changing its velocity to intensify the filtration drying process. It is also worth noting that the obtained kinetic curves are characterized by two conditional drying periods: the first and the second, which are clearly indicated in Figs. 2–4.

In order to determine the value of the critical moisture content of the studied material w^c_{cr} reached by the mass transfer zone of the perforated baffle of the laboratory installation container and establish its

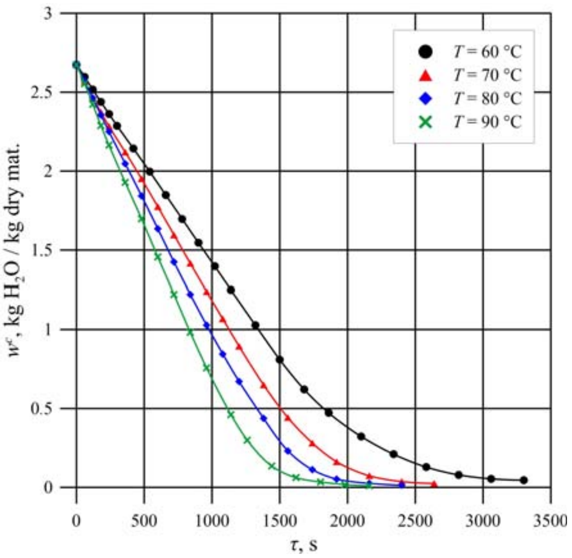

Fig. 3. Changes in the moisture content of the corn alcohol distillery stillage over time depending on the temperature of the thermal agent (at H=120 mm, and v_0=1.76 m/s)

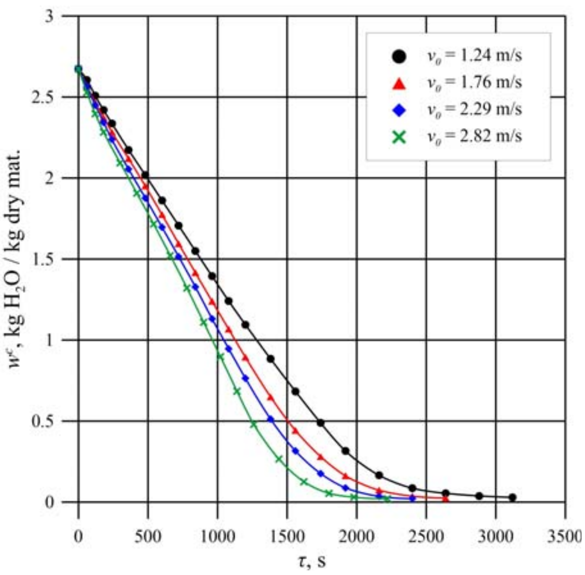

Fig. 4. Changes in the moisture content of the corn alcohol distillery stillage over time dependence on the velocity of the thermal agent (at H=120 mm and T=70⁰C)

dependence on various parameters under study such as the height of the wet material, the velocity of the thermal agent, and its temperature, it is necessary to represent the previously obtained experimental results (Figs. 2–4) in the form of dependences in the coordinates $\lg(w^c - w^c_e)$ vs. τ (Figs. 5–7).

Using the graph-analytical method, it was summarized the first and second drying periods using straight lines (Figs. 5–7). By obtaining the intersection point of these lines and approximating it to each of the axes of the graph, we calculated the logarithm of the critical moisture content of the material lg w_c and the critical drying time in the first period τ_{cr}.

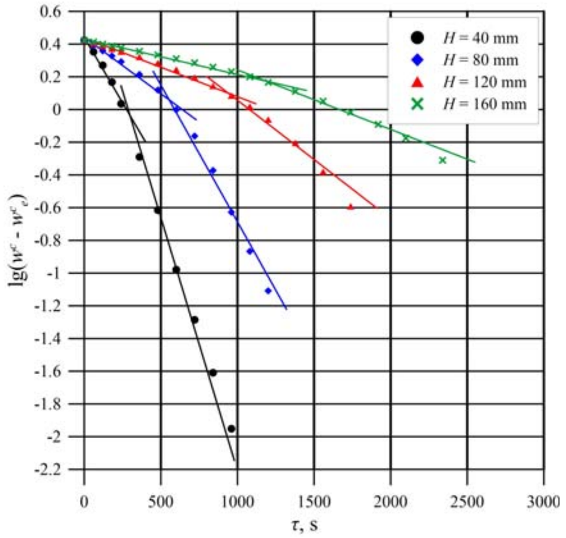

Fig. 5. Graphical dependences lg($w^c-w^c_e$) vs. τ for determining the critical moisture content w^c_{cr} and the time of its reaching τ_{cr} at different layer heights H of the corn alcohol distillery stillage filtration drying

Thus, in accordance with the chosen method, the critical moisture content can be calculated using the dependence:

$$w^c_{cr}=10^x+w^c_e, \quad (3)$$

where x=lg($w^c-w^c_e$) is the ordinate of the intersection of two lines corresponding to the first and second drying periods.

Additionally, the equilibrium moisture content of corn alcohol distillery stillage w^c_e was determined, based on the experimental data obtained, as the lowest value of the material's moisture content achieved. Since the equilibrium moisture content depends on the thermodynamic potential of the system, its value will vary with the temperature of the drying agent. At the drying temperatures of 60^0C, 70^0C, 80^0C, and 90^0C, the equilibrium moisture content is, respectively: 0.01, 0.014, 0.025, and 0.046 kg H_2O/kg dry material.

The graphically determined values of the critical moisture content w^c_{cr}, as well as the time of its reaching τ_{cr}, were summarized in Table 1.

Based on the data from Table 1, it can be concluded that the studied parameters of filtration drying influence the change in the critical moisture content of the corn alcohol distillery stillage. There is an increase in the critical moisture content with an increase in the layer height of the studied material, and its decrease with an increase in the parameters of the process thermal agent.

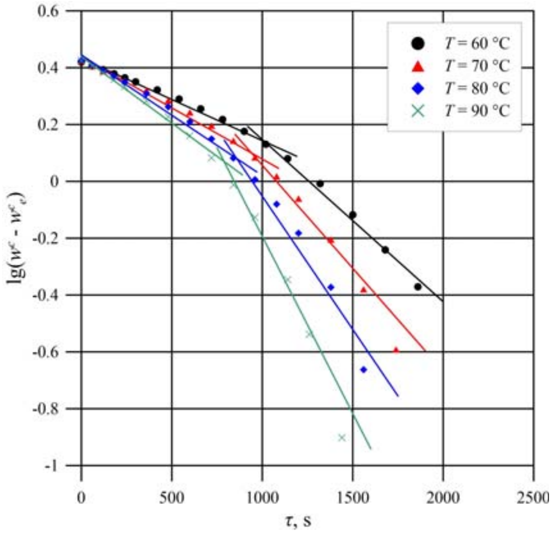

Fig. 6. Graphical dependences lg($w^c-w^c_e$) vs. τ for determining the critical moisture content w^c_{cr} and the time of its reaching τ_{cr} at different temperatures of the thermal agent T of the corn alcohol distillery stillage filtration drying

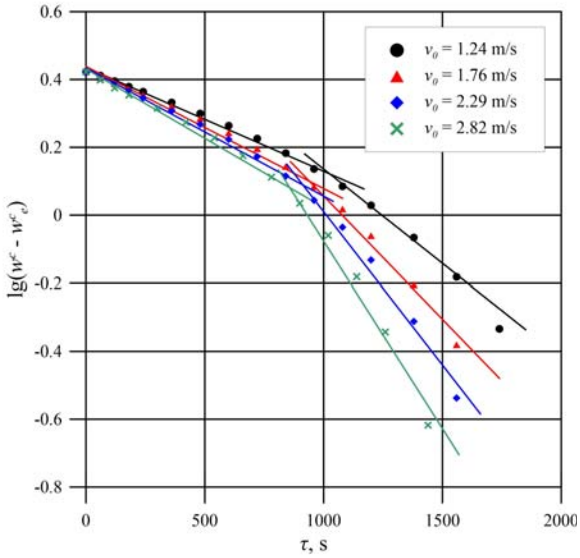

Fig. 7. Graphical dependences lg($w^c-w^c_e$) vs. τ for determining the critical moisture content w^c_{cr} and the time of its reaching τ_{cr} at different velocities of the thermal agent v_0 of the corn alcohol distillery stillage filtration drying

The description of the kinetic regularities of the filtration drying process of the alcohol distillery stillage in the period of complete saturation of the thermal agent with moisture can be carried out by determining the kinetic coefficients a and h by plotting a graphical dependence in the coordinates ln((1−w^c/w^c_0)/τ) vs. H [11] (Fig. 8).

The values of the graphically determined kinetic coefficients a and η are given in Table 2.

Table 1

The value of the critical moisture content of corn alcohol distillery stillage w^c_{cr} and the time of its reaching τ_{cr} of the corn alcohol distillery stillage filtration drying

H, mm	T, ^{0}C	ν_0, m/s	$lg(w^c - w^c_e)$	w^c_{cr}, kg H_2O/kg dry material	τ_{cr}, s
40	70	1.76	–0.038	0.941	290
80			0.06	1.173	550
120			0.1	1.284	930
160			0.171	1.508	1190
120	60		0.139	1.423	1010
	80		0.08	1.216	870
	90		0.071	1.188	780
	70	1.24	0.122	1.349	1010
		2.29	0.088	1.250	910
		2.82	0.081	1.230	850

Table 2

Dependence of the kinetic coefficients a and h on the parameters of the filtration drying process of the corn alcohol distillery stillage

No. of the line	H, mm	T, ^{0}C	ν_0, m/s	a, 1/m	lnη	η, 1/s
1	40	70	1.76	14.606	–5.576781345	0.003784728
	80					
	120					
	160					
2	120	50			–5.893278945	0.002757919
3		80			–5.596894762	0.003709364
4		90			–5.414149522	0.004453123
5		70	1.24		–5.907264389	0.002719617
6			2.29		–5.601495147	0.003692339
7			2.82		–5.445685289	0.004314882

Based on the obtained data in Table 2, let's find the numerical values of the kinetic equation (1) coefficients A, m, and n for the first drying period of alcohol distillery stillage according to the methodology described in ref. [11]. By solving the system of three equations in a matrix manner, it was obtained:

$$A=2.086\cdot10^{-4},\ m=0.645,\ \text{and}\ n=0.278.$$

Thus, the kinetic coefficient η for corn alcohol distillery stillage can be calculated using dependence:

$$\eta=2.086\cdot10^{-4}\cdot T^{0.645}\cdot\nu_0^{0.278}. \quad (4)$$

Taking into account that m>n, it can be seen that the temperature of the thermal agent has a more significant effect than its velocity on the filtration drying process, which confirms the previous conclusions of the analysis of the graphical dependences of Figs. 2–4.

Thus, substituting the values of the kinetic coefficients into dependence (1), we obtain the equation describing the intensity of filtration drying of the corn alcohol distillery stillage in the first drying period of complete saturation of the thermal agent with moisture until w^c_{cr} is reached:

$$w^c=w^c_0\cdot(1-2.086\cdot10^{-4}\cdot T^{0.645}\cdot\nu_0^{0.278}\cdot\tau\cdot e^{-14.606H}). \quad (5)$$

To describe the kinetic regularities of the second drying period, it is necessary to find the drying rate coefficients K, which are equal to the tangents of the line slope for the graphical dependencies $\ln((w^c-w^c_e)/(w^c_{cr}-w^c_e))$ vs. $(\tau-\tau_r)$ (Figs. 9–11).

The drying rate N can be calculated according to the following relationship [11]:

$$N=(w^c_0-w^c_{cr})/\tau_{cr}. \quad (6)$$

The calculated values of the coefficients K and N are given in Table 3.

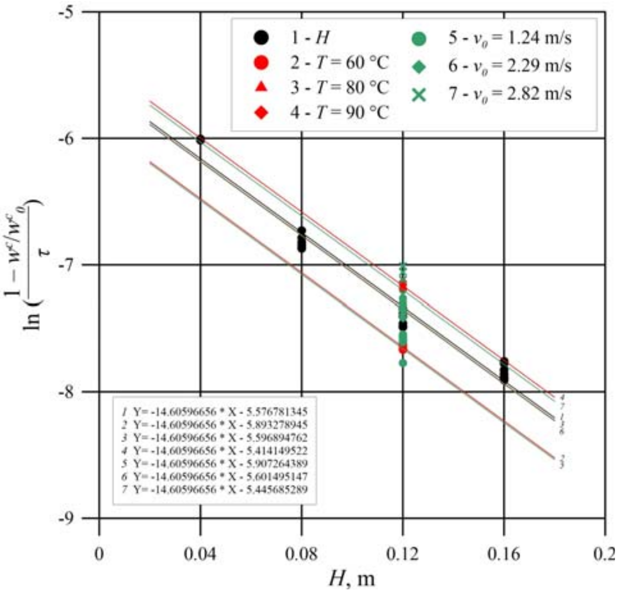

Fig. 8. Determination of the a and η coefficients in the first drying period of alcohol distillery stillage by the graphical method

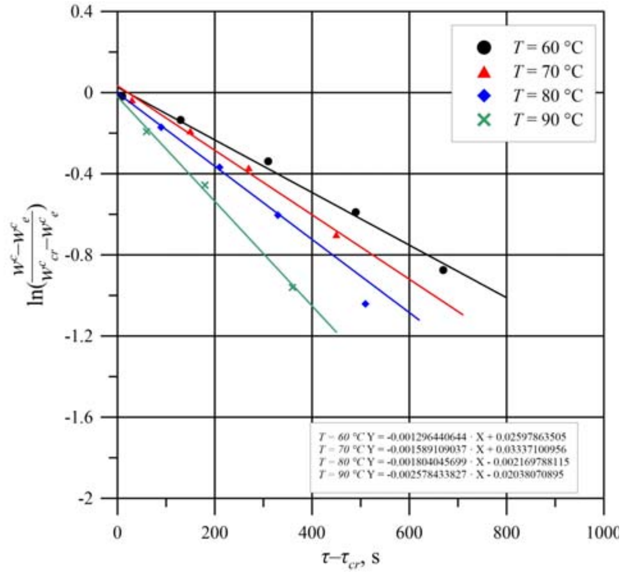

Fig. 10. Determination of the drying rate coefficient K by graphical analysis in the second drying period of the corn alcohol distillery stillage for layers of different temperatures of the thermal agent T

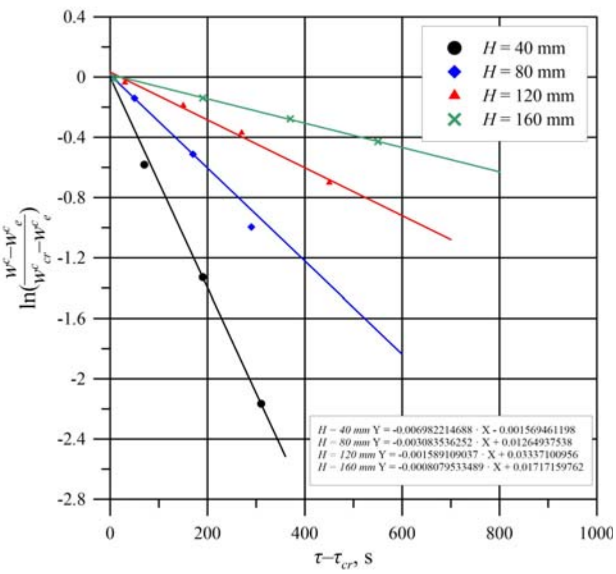

Fig. 9. Determination of the drying rate coefficient K by graphical analysis in the second drying period of the corn alcohol distillery stillage for layers of different heights H

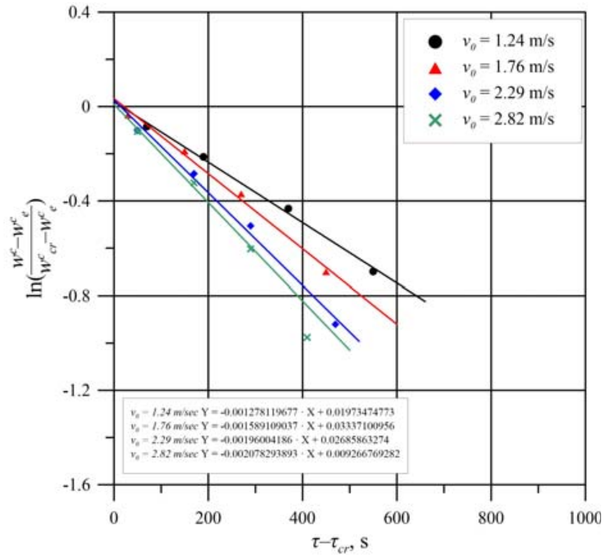

Fig. 11. Determination of the drying rate coefficient K by graphical analysis in the second drying period of the corn alcohol distillery stillage for layers of different velocities of the thermal agent ν_0

Based on the obtained values of the coefficients K and N (Table 3), the graphical dependence K vs. N was plotted (Fig. 12).

Using the obtained graphical dependence shown in Fig. 12, it was determined that the value of the relative drying coefficient χ is the tangent of the line slope to the abscissa axis, which for the crushed corn alcohol distillery stillage is equal χ=1.187 kg H_2O/kg dry material.

Thus, dependence (7) for the second drying period was obtained, which can be used to calculate the change in the moisture content of corn alcohol distillery stillage over time during the period of partial saturation of the thermal agent with moisture until the equilibrium moisture content with the thermal agent is reached.

Table 3

Dependence of the coefficients K and N on the parameters of the filtration drying process of corn alcohol distillery stillage

H, mm	T, ^{0}C	v_0, m/s	K, 1/s	N, kg H_2O/kg dry material
40	70	1.76	0.006982214688	0.005973793
80			0.003083536252	0.002728000
120			0.001589109037	0.001493978
160			0.0008079533489	0.000979328
120	60		0.001296440644	0.001238020
	80		0.001804045699	0.001675172
	90		0.002578433827	0.001904359
	70	1.24	0.001278119677	0.001311287
		2.29	0.00196004186	0.001564176
		2.82	0.002078293893	0.001698118

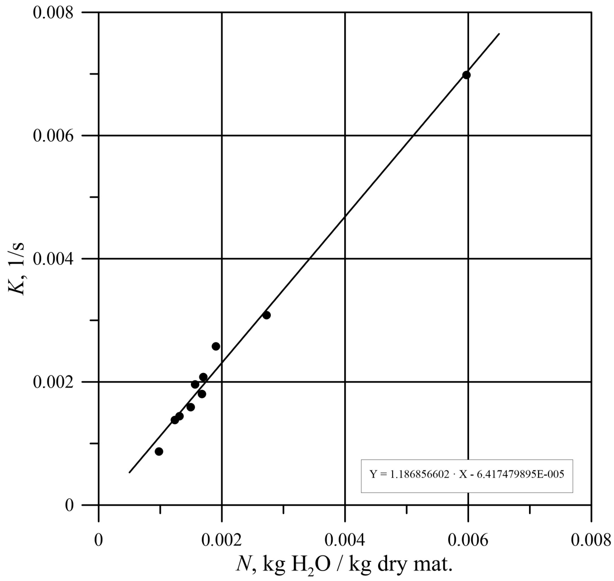

Fig. 12. Establishing the relationship between the drying coefficient K and the drying rate N in the second drying period for the corn alcohol distillery stillage

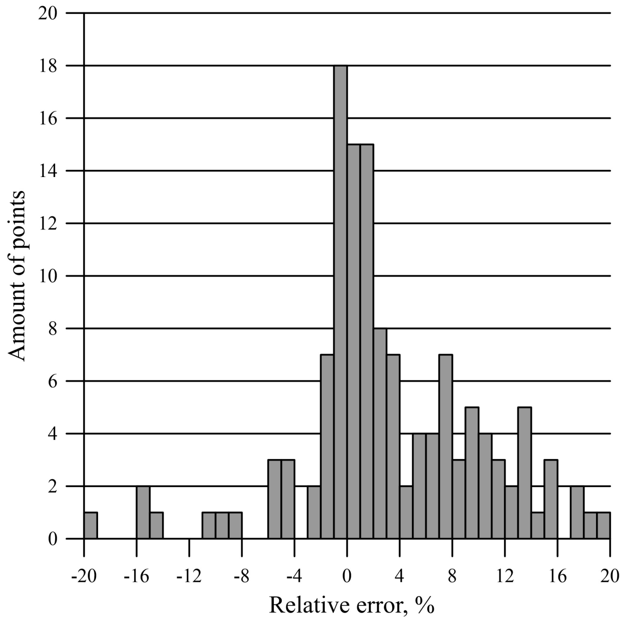

Fig. 13. Graphical distribution of the error amount to their values for the corn alcohol distillery stillage at the stationary layer height H=120 mm

$$w^c=(w^c_{cr}-w^c_e)\cdot e^{-1.187N\cdot(\tau-\tau cr)}+w^c_e. \quad (7)$$

To assess the correspondence between the experimental data and theoretically calculated ones, a graphical distribution of errors was constructed (Fig. 13). The maximum value of the relative error is 19.42%, and the average relative error is 5.37%, which makes it possible to use the obtained dependencies for the calculation of drying equipment.

Analyzing the distribution of errors between the experimental and theoretically determined values of the moisture content w^c of the corn alcohol distillery stillage (Fig. 13), it is observed that a significant number of errors are concentrated in the range up to 2%, while at the same time, their number decreases with increasing error magnitude. This distribution may be explained by the heterogeneity of the biomass.

The drying time of the corn alcohol distillery stillage τ_I in the first period will be determined according to equation (1):

$$\tau_I=(1-w^c/w^c_0)/(2.086\cdot10^{-4}\cdot T^{0.645}\cdot v_0^{0.278}\cdot\tau\cdot e^{-14.606H}), \quad (8)$$

and its drying time in the second period τ_{II} according to dependence (2):

$$\tau_{II}=(1.187\cdot(w^c_0-w^c_{cr})-\ln((w^c-w^c_e)/(w^c_{cr}-w^c_e))/(1.187\cdot N). \quad (9)$$

The total time of filtration drying of the corn alcohol distillery stillage from the initial to the final moisture content can be calculated as the sum of times τ_I and τ_{II}.

Conclusions

The paper presents the results of experimental studies of the kinetic regularities and the filtration drying process of corn alcohol distillery stillage at variable process parameters: the wet material height (40 mm, 80 mm, 120 mm, and 160 mm), the temperature of the thermal agent (60^0C, 70^0C, 80^0C, and 90^0C), and its velocity (1.24 m/s, 1.76 m/s, 2.29 m/s, and 2.82 m/s).

The experimental data of the drying process were processed by the graph-analytical method and calculation dependences were proposed, which make it possible to determine the intensity of the filtration drying process of the corn alcohol distillery stillage in two conditional drying periods, as well as the dependencies for determining the drying time of the corn alcohol distillery stillage in both drying periods τ_I and τ_{II}.

The maximum value of the relative error between the experimental data and theoretically calculated data is 19.42%, and the average relative error is 5.37%, which is an acceptable deviation of the practical calculations conducting for experimental and industrial drying plants.

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КІНЕТИЧНІ ЗАКОНОМІРНОСТІ ПРОЦЕСУ ФІЛЬТРАЦІЙНОГО СУШІННЯ КУКУРУДЗЯНОЇ ПІСЛЯСПИРТОВОЇ БАРДИ

О.С. Іващук, В.М. Атаманюк, Р.А. Чижович, С.А. Барабах

Досліджено кінетичні закономірності процесу фільтраційного сушіння кукурудзяної післяспиртової барди. Подано кінетичні криві, що характеризують процес фільтраційного сушіння кукурудзяної післяспиртової барди за різних параметрів стаціонарного шару досліджуваного матеріалу та теплового агенту: різних висотах вологого матеріалу, різних температур теплового агенту та швидкостей його руху крізь стаціонарний шар. Запропоновано розрахункові залежності для визначення інтенсивності процесу фільтраційного сушіння кукурудзяної післяспиртової барди у двох умовних періодах процесу. Наведено рівняння для розрахунку часу сушіння окремо для кожного умовного періоду сушіння. Максимальне значення відносної похибки становить 19,42%, у той час як середня відносна похибка по досліджуваних точках становить 5,37%, що є допустимим відхиленням при проведенні практичних розрахунків експериментальних та промислових сушильних установок.

Ключові слова: сушіння, фільтраційне сушіння, післяспиртова барда, кінетика, кінетичні криві, періоди сушіння, стаціонарний шар.

KINETIC REGULARITIES OF FILTRATION DRYING OF CORN ALCOHOL DISTILLERY STILLAGE

O.S. Ivashchuk *, V.M. Atamanyuk, R.A. Chyzhovych, S.A. Barabakh

Lviv Polytechnic National University, Lviv, Ukraine

*** e-mail: oleksandr.s.ivashchuk@lpnu.ua**

We studied the kinetic regularities of filtration drying of corn alcohol distillery stillage. The kinetic curves characterizing the process of filtration drying of corn alcohol distillery stillage at different parameters of the stationary layer of the studied material and thermal agent were obtained: at different heights of the wet material, and at different temperatures of the thermal agent and the velocity of its movement through the stationary layer. The calculated dependences for determining the intensity of the filtration drying process in two conditional drying periods were proposed. The equations for the calculation of drying time separately for each conditional drying period were given. The maximum value of the relative error is 19.42%, while the average relative error is 5.37%, which is an acceptable deviation in practical calculations of experimental and industrial drying installations.

Keywords: drying; filtration drying; alcohol distillery stillage; kinetics; kinetic curve; drying period; stationary layer.

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