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KINETIC REGULARITIES OF THE FILTRATION DRYING OF BARLEY BREWER'S SPENT GRAIN

Oleksandr Ivashchuk[1,✉], Volodymyr Atamanyuk[1], Roman Chyzhovych[1], Vladyslava Manastyrska[1], Serhii Barabakh[1], Zoriana Hnativ[1]

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Abstract. The paper describes the study of the kinetics of filtration drying of barley brewer's spent grain. The dependencies of the process at different parameters of the stationary layer and the thermal agent are presented: different heights of the wet material H (40 mm, 80 mm, 120 mm, and 160 mm), different temperatures of the thermal agent T (50 °C, 70 °C, 80 °C, and 90 °C), and the velocities of the thermal agent through the stationary layer of material v_0 (1.26 m/s, 1.55 m/s, 1.81 m/s, 2.31 m/s, and 2.82 m/s). The kinetic regularities of two drying periods were determined: the period of complete saturation of the thermal agent with moisture and the period of partial saturation of the thermal agent with moisture. The calculation dependencies describing the intensity of the filtration drying process in both periods are proposed. The equations for determining the drying time of barley brewer's spent grain τ_I and τ_{II} during both periods are proposed. The absolute value of the maximum relative error of the experimental values of moisture content from the theoretically calculated ones is 19.83 %, and the average value of the relative error is 3.15 %, which is acceptable for practical design calculations of drying equipment.

Keywords: drying, filtration drying, brewer's spent grains, kinetics, stationary layer.

1. Introduction

Brewer's spent grain (BSG) is a by-product formed during the filtration of beer wort from solid grain particles in the brewery.[1] BSG is a solid residue consisting of husks, pericarp particles, and a seed coat of malt grain.[2]

BSG is the main by-product of the brewing industry and accounts for approximately 85 % of all waste.[3,4] Beer consumption in the world is growing, and so is the volume of brewer's spent grain produced – currently, more than 30 million tons are produced annually.[5]

The principles of rational environmental management require the reuse of by-products.[6] It is known that BSG can be used for food purposes, as a feed additive for animals,[3,4,7-12] for fertilizing agricultural land,[4,13] for producing biogas[3,4,14] and bioethanol,[14] as adsorbent material,[14] as a source for producing phenolic compounds,[15] for alternative solid fuels,[2] *etc*.

Due to its high moisture content (~70 wt.%), BSG has a limited shelf life, storage, and transportation, which averages 2–3 days.[2]

Drying biomass of natural origin to 7÷14 wt.% is one of the effective ways to extend its use.[16] Drying of the BSG allows fuller use of its significant accumulated volumes.

Drying is a complex heat and mass transfer process that is widely used in the final stages of various production lines. The organization of the drying process has a significant impact on both the quality and cost of finished products. It is known that 8÷10 % of the world's energy is consumed by drying processes, which usually use 2.5÷3 times more energy than is required to convert moisture into steam.[17]

Given this, filtration drying is a promising method for reducing the moisture content of various materials.[18] Filtration drying is an intensive drying method that allows to increase the drying intensity and reduce specific heat and energy consumption.[19-21]

The principle of filtration drying is that the thermal agent moves through the porous structure of a gas-permeable material under a pressure drop.[18] The process of heat and mass transfer occurs on the intra-capillary surface, which exceeds the geometric surface of the dried material. In such process organization, there is mechanical moisture displacement as well as moisture removal, depending on the nature of its connection with the dried material.

The study of the kinetics of wet materials filtration drying is the primary step in determining the process parameters, its time, and optimal process modes. In ge-

[1] Department of Chemical Engineering, Institute of Chemistry and Chemical Technologies, Lviv Polytechnic National University, 12 S. Bandery St., Lviv, 79013, Ukraine
✉ *oleksandr.s.ivashchuk@lpnu.ua*

neral, the kinetics of the drying process characterizes the change in moisture content in the material with time – in fact, the drying duration. The nature of the kinetic curves is determined by the structural features of the material under study, the peculiarities of heat and mass transfer within the body and between its surface, and the environment. The kinetics of the drying process is influenced by the properties of the dried materials (moisture content, the form of moisture bonding with the material structure, *etc*.), the parameters of the thermal agent and its movement (moisture content, temperature, velocity), and the state of the material in the drying zone (stationary, boiling, suspended). A significant number of affecting parameters complicate the theoretical calculation of the process and require experimental studies with further generalization of their results.

The main purpose of this work was to conduct experimental studies aimed at determining the effect of the main process parameters (height of the wet material *H*, temperature of the thermal agent *T*, velocity of the thermal agent v_0) on the filtration drying of barley brewer's spent grain and further generalization of the obtained data.

2. Experimental

The filtration drying process of barley brewer's spent grain (Fig. 1) obtained at the production line of the Kumpel brewery (Lviv, Ukraine)[2] was studied.

Fig. 1. The dried barley brewer's spent grain

To study the filtration drying process, an experimental laboratory setup was used (Fig. 2), which makes it possible to conduct comprehensive studies of drying wet material by changing the height of its layer, the velocity of the thermal agent, and its temperature.[18]

The setup shown in Fig. 2 consists of fan *1* that blows air into an electric heater *2*, where it is heated to a predetermined temperature. Passing through diffuser *3*, the air enters container *5* with a layer of the tested material. A thermocouple *4* is located above the container to determine the air temperature at the outlet of the diffuser. The thermocouple is connected to a SENTOS D1S control and measuring device, which establishes and maintains a constant temperature of the drying agent. A vacuum gauge *8* is installed to measure the pressure loss in the tested material layer. Container *5* is connected to receiver *6*, in which a vacuum is created by a water-ring vacuum pump *12*. Rotameter *9* is located in front of the previous one to measure airflow. There is also a control valve *10* (to regulate the flow of the thermal agent) and a shut-off valve *11*.[18]

The moisture content of the initial samples was determined using the RADWAG MA 50/1.R moisture analyzer according to the method described in [18]. The height of the wet material layer in container *5* was determined using the bulk density data. The method for determining the bulk density of raw materials is also described in [18]. A schematic view of container *5* is given in the literature.[22]

To study the kinetics of filtration drying of barley brewer's spent grain, three series of experiments were conducted, the peculiarity of which was the change in a certain process parameter – the temperature of the thermal agent *T*, the velocity of the thermal agent v_0, and the height of the wet material layer *H*.

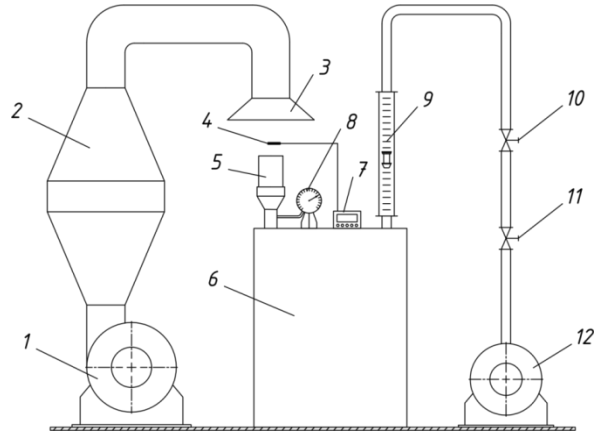

Fig. 2. Schematic view of the experimental setup for filtration drying: 1 – fan; 2 – electric heater; 3 – diffuser; 4 – thermocouple; 5 – container; 6 – receiver; 7 – SENTOS D1S control and measuring device; 8 – vacuum gauge; 9 – rotameter; 10 – control valve; 11 – shut-off valve; 12 – water-ring vacuum pump

It is known that the drying process of dispersed materials is divided into two periods:[19] the first period is a complete saturation of the thermal agent with moisture,

and the second period is a partial saturation of the thermal agent with moisture. To determine the values of the critical moisture content w^c_{cr} and the critical time τ_{cr} at different temperatures of the thermal agent and different filtering rates of the thermal agent, the renowned method was used.[19,23] This method is based on the construction of kinetic curves in the coordinates $lg\ (w^c - w^c_e) = f(\tau)$, where w^c is the running value of the moisture content of the 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; τ is the drying time, s.

According to the theory,[19] the dependence describing the filtration drying kinetics of barley brewer's spent grain in the first period of complete saturation of the thermal agent with moisture until the wet material reaches the critical moisture content w^c_{cr} is as follows:

$$\frac{w^c}{w^c_0} = 1 - \eta \cdot \tau \cdot e^{-a \cdot H} \quad (1)$$

where η is the kinetic coefficient; w^c_0 is the initial value of the material moisture content, kg H_2O / kg dry material.

If equation (1) is represented in the form:

$$\frac{1-\frac{w^c}{w^c_0}}{\tau} = \eta \cdot e^{-a \cdot H} \quad (2)$$

and marked as

$$\frac{1-\frac{w^c}{w^c_0}}{\tau} = y, \quad (3)$$

then, accordingly, Eq. (2) can be expressed as:

$$y = \eta \cdot e^{-a \cdot H} \quad (4)$$

After logarithmizing Eq. (4), we obtain:

$$\ln(y) = \ln(\eta) - a \cdot H \quad (5)$$

The kinetic coefficients a and η are determined by graph-analytical methods in the coordinates $ln\ ((1 - w^c/w^c_0)/\tau) = f\ (H)$, where a is the slope to the abscissa axis, and $ln(\eta)$ is the segment cut off on the ordinate axis.

Since in the first drying period, the change in the moisture content of the dispersed material is limited by the external drying conditions (the velocity and temperature of the thermal agent), the coefficient η can be represented in general by Eq. (6):

$$\eta = A \cdot T^m \cdot v_0^n, \quad (6)$$

where the coefficients A, m and n are constant for a given material and are determined on the basis of generalizing the results of experimental studies with different parameters of the drying process.

Thus, for the period of complete saturation of the thermal agent with moisture, the kinetic equation of the drying process (1) takes the form:

$$\frac{w^c}{w^c_0} = 1 - A \cdot T^m \cdot v_0^n \cdot \tau \cdot e^{-a \cdot H} \quad (7)$$

In the second period, when the thermal agent is partially saturated with moisture, another equation[19] will be valid:

$$-\frac{dw^c}{d\tau} = K \cdot (w^c - w^c_e), \quad (8)$$

where K is the drying coefficient, 1/s:

$$K = \chi \cdot N$$

where 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).

Integrating equation (8), we obtain

$$\frac{w^c - w^c_e}{w^c_{cr} - w^c_e} = e^{-K \cdot (\tau - \tau_{cr})} \quad (9)$$

where w^c_{cr} is the critical moisture content of wet material, kg H_2O / kg dry material, τ_{cr} is the critical drying time, s.

After logarithmizing Eq. (9), we get the following expression:

$$ln\ \frac{w^c - w^c_e}{w^c_{cr} - w^c_e} = -K \cdot (\tau - \tau_{cr}) \quad (10)$$

Thus, to find the drying coefficient K, it is necessary to plot a graphical dependence in the coordinates $ln((w^c - w^c_e)/(w^c_{cr} - w^c_e)) = f(\tau - \tau_{cr})$, from which this coefficient is determined as the slope to the abscissa axis.

The drying rate N can be determined by the equation:

$$N = \frac{w^c_0 - w^c_{cr}}{\tau_{cr}} \quad (11)$$

To determine the relative drying coefficient χ, it is necessary to plot the graphical dependence $K = f(N)$.

The kinetic equation for the second drying period (9) in its final form is written as

$$w^c = (w^c_{cr} - w^c_e) \cdot e^{-\chi \cdot N \cdot (\tau - \tau_{cr})} + w^c_e \quad (12)$$

The time of reaching the critical moisture content of the crushed material in the first period is written in the form (13), provided that $w^c \geq w^c_{cr}$, $\tau \geq \tau_{cr}$:

$$\tau_I = \frac{1-\frac{w^c}{w^c_0}}{A \cdot T^m \cdot v_0^n \cdot e^{-a \cdot H}} \quad (13)$$

and in the period of partial saturation of the thermal agent with moisture based on Equation (12):

$$\tau_{II} = \frac{\chi \cdot (w^c_0 - w^c_{cr}) - ln(\frac{w^c - w^c_e}{w^c_{cr} - w^c_e})}{\chi \cdot N} \quad (14)$$

The total time of filtration drying of the wet material from the initial moisture content to the final moisture content will be the sum of the values of equations (13) and (14).

3. Results and Discussion

The parameters of the brewer's spent grain under study were as follows: the initial moisture content 77.88 %, bulk density 451.74 kg/m^3. The change in the moisture content of barley brewer's spent grain was studied at different parameters of the stationary layer and the thermal agent: different heights of the wet material H (40 mm, 80 mm, 120 mm, and 160 mm), different temperatures of the thermal agent T (50 °C, 70 °C, 80 °C,

and 90 °C), and the velocities of the thermal agent through the stationary layer of material v_0 (1.26 m/s, 1.81 m/s, 2.31 m/s, and 2.82 m/s). When one of the studied parameters H, T, v_0 was changed, the other two parameters remained unchanged. For comparison, the average values of the studied parameters were chosen as unchanged: H = 120 mm, T = 70 °C, v_0 = 1.81 m/s. The results of the experimental studies are shown in Figs. 3–5.

Fig. 3 shows that the drying time increases with an increase in the height of the wet material layer. If for H = 40 mm the final moisture content is reached in about 2000 s, then for H = 160 mm it is reached in about 5000 s. Thus, with a 4 times increase in the height of the wet material layer, the drying time increases by ~ 2.5 times.

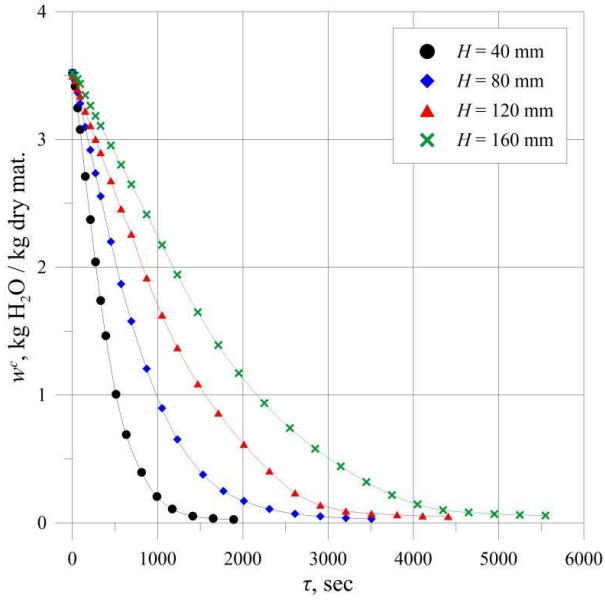

Fig. 3. Changes in the moisture content of a stationary layer of barley brewer's spent grain over time at different heights of wet material (at T = 70 °C, v_0 = 1.81 m/s)

The drying kinetic curves of brewer's spent grain in Fig. 4 indicate a significant decrease in drying time (from ~7400 s to ~2400 s) with increasing temperature (from 50 °C to 90 °C).

When studying the changes in the thermal agent velocity (Fig. 5), we observed that the kinetic curves are unevenly distributed with an approximately proportional change in the thermal agent velocity v_0 (1.26 m/s, 1.81 m/s, 2.31 m/s, 2.82 m/s) – approximately 0.5 m/s. The process of filtration drying at an additional velocity of v_0 = 1.55 m/s was studied. According to the experimental data, above the velocity v_0 = 1.81 m/s there is practically no effect on the drying time. In general, increasing the velocity of the thermal agent through a stationary layer of wet material has a positive effect on the rate of the drying process and reduces its time (Fig. 5).

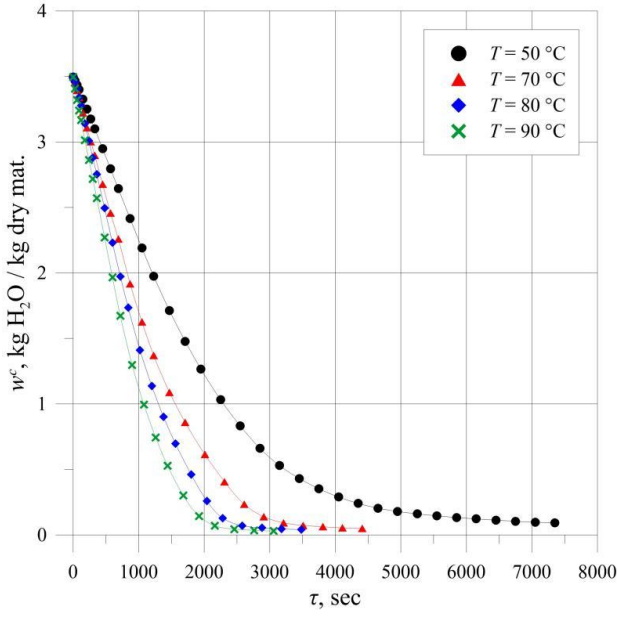

Fig. 4. Changes in the moisture content of a stationary layer of barley brewer's spent grain over time at different temperatures of the thermal agent (at H = 120 mm, v_0 = 1.81 m/s)

In general, analyzing Figs. 3–5, it can be concluded that the temperature of the thermal agent has a more significant effect on the intensity of the drying process compared to the change in the velocity of the thermal agent. It is also noticeable that under different parameters of the drying process of barley brewer's spent grain, the obtained kinetic curves are characterized by clearly defined first and second periods of the drying process.

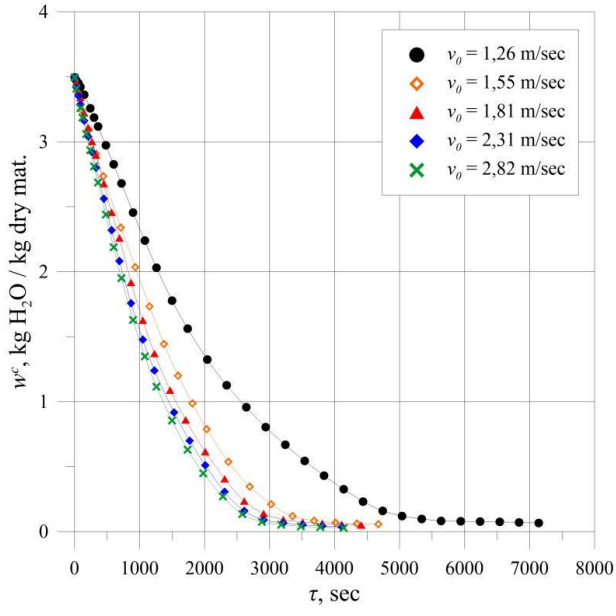

Fig. 5. Changes in the moisture content of a stationary layer of barley brewer's spent grain over time at different velocities of the thermal agent (at H = 120 mm, T = 70 °C)

To determine the value of the critical moisture content of the material w^c_{cr}, which is achieved by the mass transfer zone of the perforated baffle of the container *5* of the laboratory setup (Fig. 1) and its dependence on the studied parameters (height of the wet material, thermal agent velocity and temperature), as well as the critical drying time in the first period τ_{cr} (time when the mass transfer zone reaches the perforated baffle of the container), it is necessary to present the obtained drying results (Figs. 3–5) in the form of dependencies $lg\ (w^c - w^c_e) = f(\tau)$ (Figs. 6–8).

The first and second drying periods (Figs. 6–8) can be summarized by straight lines using the graph-analytical method. The ordinate of the point of intersection of these two lines will correspond to the logarithm of the critical moisture content of the material lg w^c_{cr} and the abscissa will correspond to the critical drying time in the first period τ_{cr}.

Using this method of determination, the critical moisture content of the material w^c_{cr} is calculated according to the equation:

$$w^c_{cr} = 10^{x} + w^c_e , \qquad (15)$$

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.

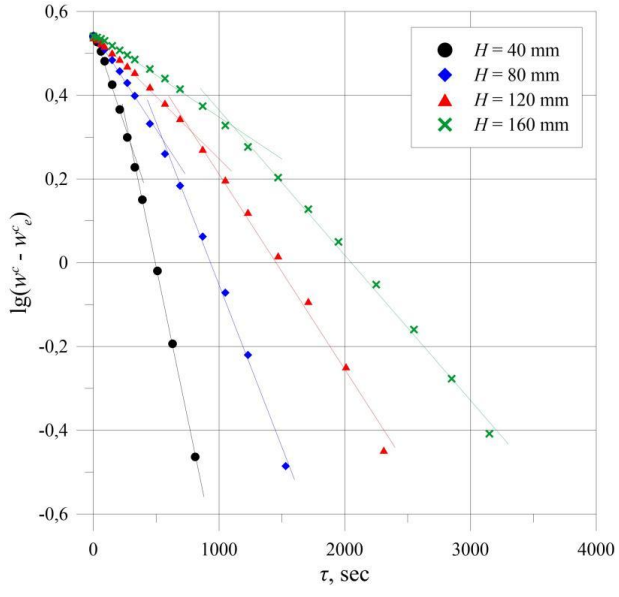

Fig. 6. Graph-analytical method for determining the critical moisture content w^c_{cr} and the time of its achievement τ_{cr} for layers of different heights *H* of barley brewer's spent grain

For the calculations, it was additionally necessary to determine the value of the equilibrium moisture content of the barley brewer's spent grain w^c_e. The equilibrium moisture content depends on the thermal potential of the system and, as a result, is variable for different temperatures. The equilibrium moisture content was conditionally taken as the lowest value for the achieved moisture content at the temperature of the drying process during the experimental studies, for 50 °C, 70 °C, 80 °C, and 90 °C, values w^c_e were 0.09, 0.05, 0.04, and 0.03 kg H_2O/kg dry material, respectively.

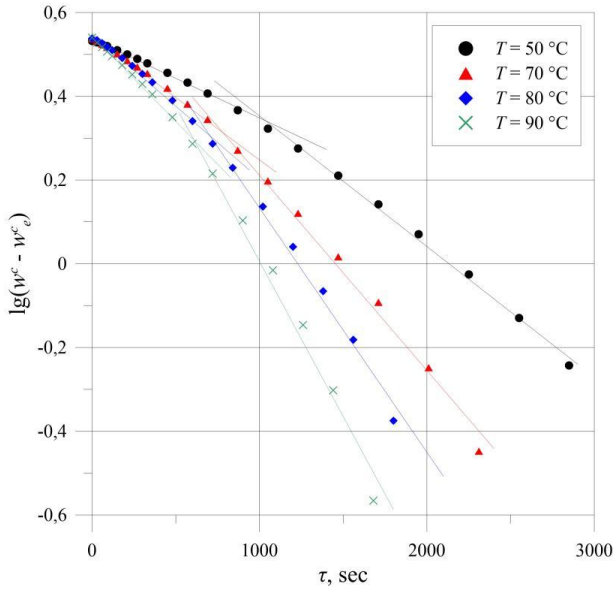

Fig. 7. Graph-analytical method for determining the critical moisture content w^c_{cr} and the time of its achievement τ_{cr} at different temperatures of the thermal agent *T*

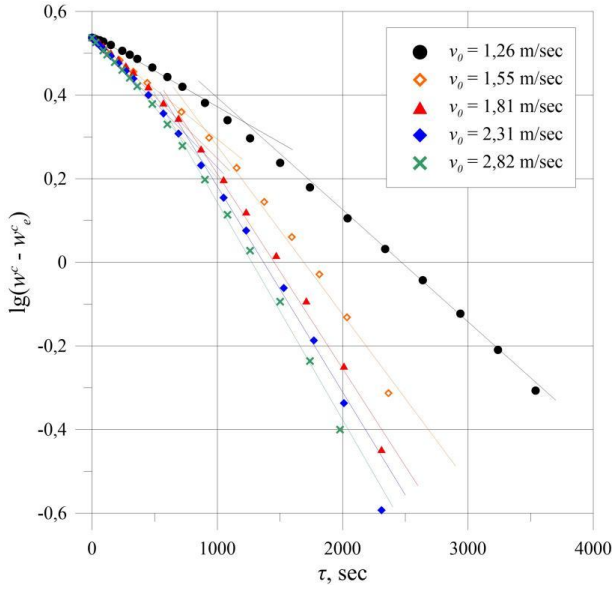

Fig. 8. Graph-analytical method for determining the critical moisture content w^c_{cr} and the time of its achievement τ_{cr} for different velocities of the thermal agent v_0

The determined data of the critical moisture content w^c_{cr} and the time of its achievement τ_{cr} are summarized in Table 1.

Table 1. Values of critical moisture content of barley brewer's spent grain w^c_{cr} and time of its achievement τ_{cr}

H, mm	T, °C	v_0, m/s	$lg\ (w^c - w^c_e)$	w^c_{cr}, kg H_2O / kg dry material	τ_{cr}, s
40	70	1.81	0.289	1.995	280
80			0.295	2.022	550
120			0.313	2.106	780
160			0.325	2.163	1120
120	50		0.341	2.283	1040
	80		0.304	2.054	720
	90		0.296	2.007	590
	70	1.26	0.334	2.208	1210
		1.55	0.318	2.13	890
		2.31	0.306	2.073	750
		2.82	0.301	2.05	710

Table 2. Dependence of the kinetic coefficients a and η on the parameters of the filtration drying process of barley brewer's spent grain

No. of the line	H, mm	T, °C	v_0, m/s	a, 1/m	$ln(\eta)$	η, 1/s
1	40	70	1.81	12.136	-6.138657042	0.00215782
	80					
	120					
	160					
2	120	50			-6.635556812	0.001312848
3		80			-6.234698152	0.001960221
4		90			-5.689815876	0.003380215
5		70	1.26		-6.742571554	0.00117961
6			1.55		-6.095589861	0.002252781
7			2.31		-5.871264487	0.002819306
8			2.82		-5.798888421	0.003030922

The analysis of Table 1 shows that the critical moisture content of barley brewer's spent grain depends on the temperature and filtration rate of the thermal agent, as well as the height of the stationary layer of wet material.

To describe the kinetic regularities of filtration drying of barley brewer's spent grain in the period of complete saturation of the thermal agent with moisture, it is necessary to determine the kinetic coefficients a and η, which are defined from experimental data by plotting the graphical dependence in the coordinates $ln\ ((1 - w^c/w^c_0)/\tau) = f\ (H)$ (Fig. 9). The points are plotted only for the first drying period, i.e., up to the values of w^c_{cr} (Table 1).

The construction of graphical dependencies is carried out as follows. First, generalized line *1* (Fig. 9, Table 2) is plotted for the experimental data at different heights H of the stationary layer of wet material. The kinetic coefficient a is defined as the slope of the straight line (Fig. 9). The value of $ln(\eta)$ will correspond to the intersection of the straight line with the ordinate axis. It is known that the coefficient a is constant for the material[23,24] and, accordingly, the slope of line *1* will be the same for all lines, so the following lines are plotted as averaged in parallel for the data of experimental studies at different temperatures of the thermal agent (lines 2–4) and velocities of the thermal agent (lines 5–8).

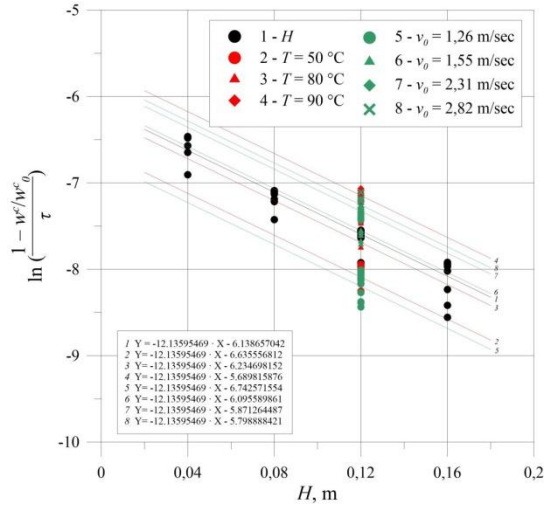

Fig. 9. Graphical determination of the coefficients a and η in the first drying period

The results of the determination of the kinetic coefficients a and η are given in Table 2.

Let us form a system of three equations, the solution of which will allow us to find the coefficients *A*, *m* and *n* for equation (6). The created system of equations (16) contains different values of η for different parameters of the filtration drying process of barley brewer's spent grain – the temperature of the thermal agent *T* and its velocity v_0, since it is the external drying conditions that limit the change in the moisture content of the material during the period of complete saturation of the thermal agent with moisture.[19]

$$\begin{aligned} \eta_1 &= A \cdot T_1^m \cdot v_{01}^n \\ \eta_2 &= A \cdot T_2^m \cdot v_{02}^n \\ \eta_3 &= A \cdot T_3^m \cdot v_{03}^n \end{aligned} \quad (16)$$

To solve the system of equations (16), it was represented in logarithmic form:

$$\begin{aligned} ln\eta_1 &= lnA + m \cdot lnT_1 + n \cdot lnv_{01} \\ ln\eta_2 &= lnA + m \cdot lnT_2 + n \cdot lnv_{02} \\ ln\eta_3 &= lnA + m \cdot lnT_3 + n \cdot lnv_{03} \end{aligned} \quad (17)$$

The system of equations was solved by the matrix method. Constant coefficients for brewer's spent grain were determined from the solution of the system of equations (17), according to the data of Fig. 9 and Table 2.

$A = 7.093 \cdot 10^{-7}$, $m = 1.781$, $n = 0.765$

Thus, to determine the kinetic coefficient η for barley brewer's spent grain the following equation was obtained:

$$\eta = 7.093 \cdot 10^{-7} \cdot T^{1.781} \cdot v_0^{0.765} \quad (18)$$

The obtained coefficients indicate a more significant effect of the thermal agent temperature than its velocity through a stationary layer of wet material, since $m > n$. This confirms the previous conclusion of the analysis of Figs. 3–5.

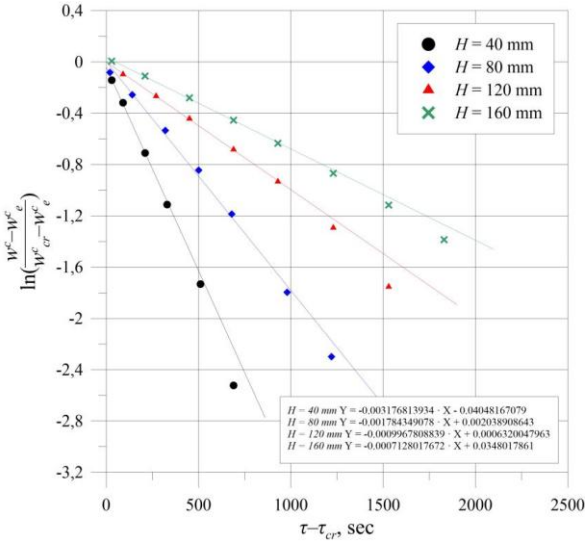

Fig. 10. Graph-analytical determination of the coefficient *K* in the second period of drying barley brewer's spent grain in layers of different heights *H*

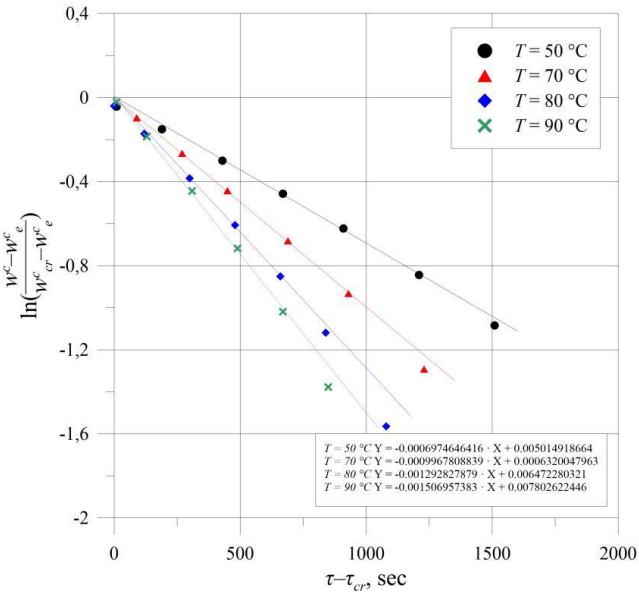

Fig. 11. Graph-analytical determination of the *K* coefficient in the second period of drying barley brewer's spent grain at different temperatures of the thermal agent *T*

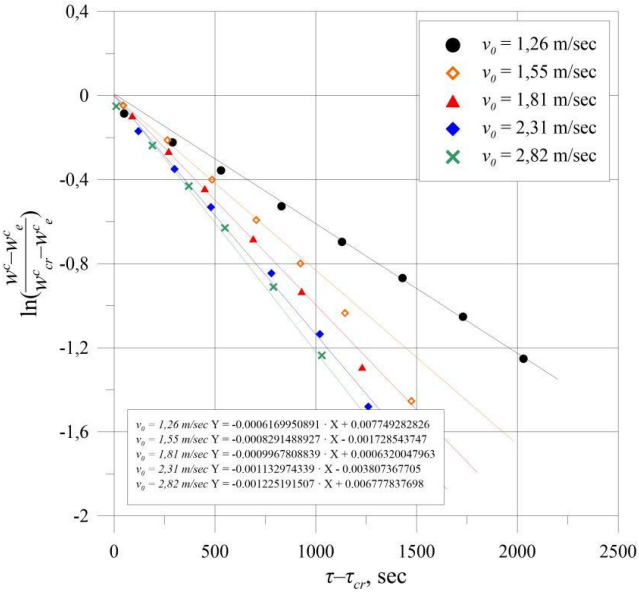

Fig. 12. Graph-analytical determination of the coefficient *K* in the second period of drying barley brewer's spent grains at different velocities of the thermal agent v_0

Thus, the dependence describing the intensity of filtration drying of barley brewer's spent grain during the first drying period of the thermal agent complete saturation with moisture until w^c_{cr} is reached has a view:

$$w^c = w_0^c \cdot (1 - 7.093 \cdot 10^{-7} \cdot T^{1.781} \cdot v_0^{0.765} \cdot \tau \cdot \cdot e^{-12.136 \cdot H}) \quad (19)$$

Regarding the second drying period, the period of partial saturation of the thermal agent with moisture, to

describe its kinetic laws, it is necessary to find the drying rate coefficient K according to Eq. (10). Let us construct the graphical dependencies $ln((w^c–w^c_e)/(w^c_{cr}–w^c_e)) = f(\tau–\tau_{cr})$, from which this coefficient will be defined as the slope to the abscissa axis (Figs. 10–12).

The drying rate N was calculated according to dependence (11). In Table 3, the corresponding values of K and N are given.

Based on Table 3, the graphical dependence $K = f(N)$ was plotted (Fig. 13).

Table 3. Dependence of the coefficients K and N on the parameters of the process of filtration drying of barley brewer's spent grain

H, mm	T, °C	v_0, m/s	K, 1/s	N, kg H_2O / kg dry material
40	70	1.81	0.003176813934	0.005449035
80			0.001784349078	0.002723600
120			0.0009967808839	0.001781260
160			0.0007128017672	0.001330373
120	50		0.0006974646416	0.001165752
	80		0.001292827879	0.002001920
	90		0.001506957383	0.002522682
	70	1.26	0.0006169950891	0.001063953
		1.55	0.0008291488927	0.001534138
		2.31	0.001132974339	0.001896510
		2.82	0.001225191507	0.002035750

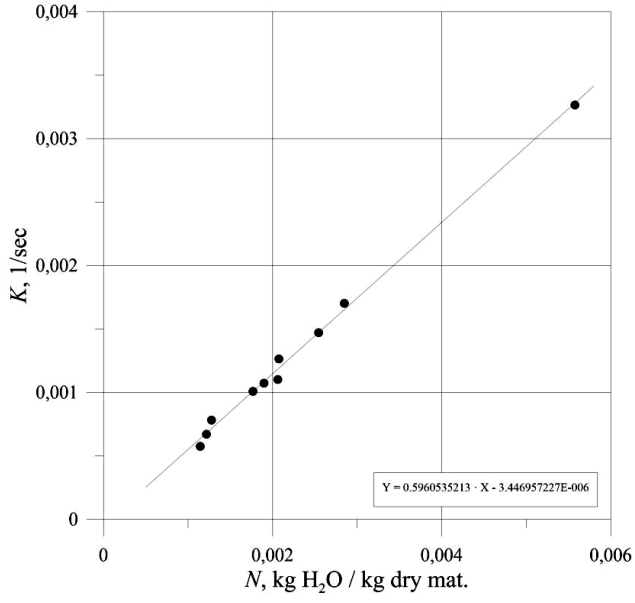

Fig. 13. Graphical dependence of the drying coefficient K on the drying rate in the period of complete saturation of the thermal agent with moisture N for filtration drying of barley brewer's spent grain

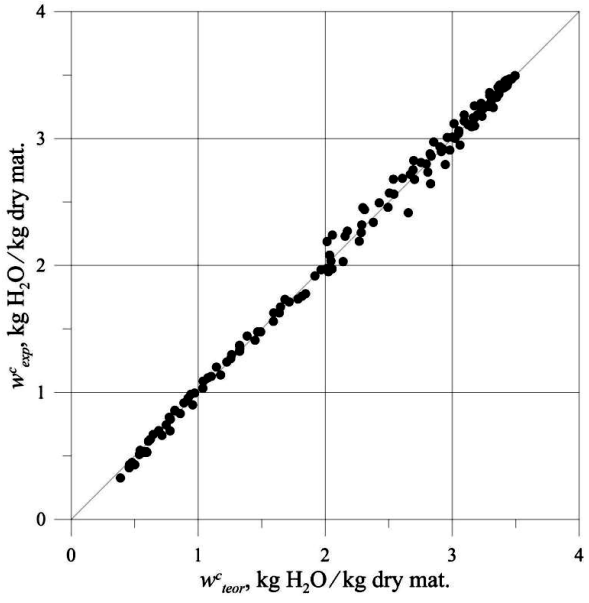

Fig. 14. Correlation between the experimentally obtained and theoretically calculated data of moisture content w^c at the stationary layer height of barley brewer's spent grain H = 120 mm

From the graphical dependence in Fig. 13, it was determined that the value of the relative drying coefficient χ is the tangent of the line slope to the abscissa, which for the barley brewer's spent grain is equal to $\chi \approx 0.596$ kg H_2O/kg dry material.

Taking into account the value of χ, dependence (12) can be represented as follows:

$$w^c = w^c_{cr} - w^c_e \cdot e^{-0.596 \cdot N \cdot \tau - \tau_{cr}} + w^c_e \qquad (20)$$

Equation (20) makes it possible to calculate the change in the moisture content of barley brewer's spent grain over time during drying in the period of partial saturation of the thermal agent with moisture until the equilibrium moisture content with the thermal agent is reached.

Let us construct a correlation (Fig. 14) between the experimentally obtained data and theoretically calculated according to Eqs (19) and (20). The resulting visualization shows that the calculated dependencies correctly describe

the process of filtration drying of barley brewer's spent grain. The absolute value of the maximum relative error of the differences between the experimental values of moisture content and theoretically calculated ones is 19.83 %, and the average relative error is 3.15 %, which is quite acceptable for practical design calculations of drying equipment. The recommended industrial values for the height of the material layer for drying are 80÷120 mm, taking into account the rational use of thermal energy and energy to create a pressure drop during drying.

The drying time of barley brewer's spent grain τ_I in the first period will be determined based on Eq. (13):

$$\tau_I = \frac{1-\frac{w^c}{w_0^c}}{7.093\cdot10^{-7}\cdot T^{1.781}\cdot v_0^{0.765}\cdot e^{-12.136\cdot H}} \quad (21)$$

and its drying time in the period of partial saturation of the thermal agent with moisture τ_{II} according to dependence (14):

$$\tau_{II} = \frac{0.596\cdot(w_0^c - w_{cr}^c) - ln(\frac{w^c - w_e^c}{w_{cr}^c - w_e^c})}{0.596\cdot N} \quad (22)$$

The total time of filtration drying of barley brewer's spent grain from the initial to the final moisture content can be calculated as the sum of (21) and (22).

4. Conclusions

Thus, the kinetic regularities of the filtration drying process of barley brewer's spent grain were studied at different process parameters – heights of wet material H (40 mm, 80 mm, 120 mm, and 160 mm), temperatures of the thermal agent T (50 °C, 70 °C, 80 °C, and 90 °C), and velocities of the thermal agent v_0 (1.26 m/s, 1.55 m/s, 1.81 m/s, 2.31 m/s, and 2.82 m/s).

As a result of the analysis of the experimental data obtained, generalizing equations were established that describe the drying intensity during the first and second drying periods – the period of complete saturation of the thermal agent with moisture and the period of partial saturation of the thermal agent with moisture.

The equation describing the intensity of filtration drying of barley brewer's spent grain in the first drying period until the critical value of moisture content w^c_{cr} is reached has a view:

$$w^c = w_0^c \cdot (1 - 7.093 \cdot 10^{-7} \cdot T^{1.781} \cdot v_0^{0.765} \cdot \cdot \tau \cdot e^{-12.136\cdot H})$$

In the second period, the change in the moisture content of barley brewer's spent grain is described by the following equation:

$$w^c = w_{cr}^c - w_e^c \cdot e^{-0.596\cdot N\cdot \tau-\tau_{cr}} + w_e^c$$

The dependencies determining the drying time of barley brewer's spent grain τ_I and τ_{II} in both drying periods were established.

The absolute value of the maximum relative error of the experimental values of moisture content from the theoretically calculated values is 19.83 %, and the average value of the relative error is 3.15 %, which is acceptable for practical design calculations of drying equipment.

Author Contributions

OI and VA had the initial idea and conceived the experiments. VA developed methods of analysis of raw materials and results. RC, VM, and SB prepared the laboratory installation. OI, RC, VM, and SB performed the experiments. OI and VA analyzed the experimental results and wrote the draft of the article. OI made graphs. ZH calculated the system of equations by the matrix method. OI and VA supervised the work.

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КІНЕТИЧНІ ЗАКОНОМІРНОСТІ ФІЛЬТРАЙЙНОГО СУШІННЯ ЯЧМІННОЇ ПИВНОЇ ДРОБИНИ

Анотація. *У статті описано дослідження кінетики фільтраційного сушіння ячмінної пивної дробини. Наведено залежності фільтраційного сушіння ячмінної пивної дробини за різних параметрів стаціонарного шару та теплового агенту: різної висоти вологого матеріалу H (40 мм, 80 мм, 120 мм, 160 мм), різних температур теплового агенту T (50 °C, 70 °C, 80 °C, 90 °C), швидкості теплового агенту через нерухомий шар матеріалу v_0 (1,26 м/с, 1,55 м/с, 1,81 м/с, 2,31 м/с, 2,82 м/с). Визначено кінетичні закономірності двох періодів сушіння: періоду повного насичення теплового агенту вологою та періоду часткового насичення теплового агенту вологою. Запропоновано розрахункові залежності, що описують інтенсивність процесу фільтраційного сушіння в обидва періоди. Запропоновано рівняння для визначення часу сушіння відпрацьованої ячмінної пивної дробини τ_I та τ_{II} в обидва періоди сушіння. Абсолютне значення максимальної відносної похибки експериментальних значень вологовмісту від теоретично розрахованих становить 19,83 %, а середнє значення відносної похибки – 3,15 %, що є прийнятним для практичних проектних розрахунків сушильного обладнання.*

Ключові слова: *сушіння, фільтраційне сушіння, пивна дробина, кінетика, стаціонарний шар.*