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KINETICS OF DIFFUSION MASS TRANSFER DURING FILTRATION DRYING OF GRAIN MATERIALS

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Abstract. The work deals with theoretical and experimental investigations concerning coefficient of moisture pore diffusion from grain during filtration drying. To determine the coefficient of pore diffusion the model was used basing on the solution of differential equation under boundary conditions of the first type. The estimated dependence of the coefficients on heat agent temperature was obtained.

Keywords: coefficient of pore diffusion, drying kinetics, moisture content, grain.

1. Introduction

Ethyl alcohol is a product which is widely used in food and chemical industry, microbiology, medicine and other branches of industry. It is well-known that cereal crops (wheat, corn, oats, millet, barley, rye, *etc*.) are used as a raw material for alcohol production. All crops must meet the following demands: moisture content is not less than 14.5 %, impurities content – no more than 5 %, bulk density – not less than 710 kg/m^3, grain admixtures – no more than 15 %. Thus it is necessary to dry the crops till the graded grain state. The drying has an essential effect on techno-economical characteristics of grain because just at this stage 80 % of all energy is consumed [1]. It is a matter of common knowledge that 8–10 % of all energy in the world is consumed for drying [2]. The drying method, grain dryer design and optimal regime are connected with material properties and have to ensure the necessary quality and properties of wheat grain under minimal consumption of energy.

The direct-fired dryers are widely used in the industry but the analysis of their operation shows their unavailability concerning energy saving, ecology and product safety [3]. While drying the sowing grain the energy consumption is greater by 1.3 times compared with that of bread grain [4]. Therefore we propose to use filtration drying (FD) as one of the most effective, intensive, low-temperature and environmentally friendly methods. The essence of the process is to filter a heat agent by the direction "moist material – perforated partition" due to pressure difference.

It is known that grain is characterized by the presence of internal moisture which is evaporated due to the internal diffusion. It is a limiting stage of drying. Hence the investigation of pore-diffusion mass transfer during grain drying is an urgent problem.

V. Atamanyuk [5] developed a mathematical model of moisture distribution in the spherical particle during its drying. On the basis of the model he determined the pore diffusion coefficient D_w and its dependence on external hydrodynamics as Eq. (1):

$$\frac{D_w}{D_0} = 2.77 \cdot 10^{-2} \cdot \mathrm{Re}^{0.32} \quad (1)$$

The pore diffusion mass transfer during FD of "energy willow" was investigated by M. Mosyuk [6]. To determine pore diffusion coefficient D_w I. Barna *et al*. [7] studied FD kinetics of single spherical granule the pores of which are kinetically equal. The dependence of D_w on temperature [6, 7] is represented by the following dependence:

$$D_w^t = D_w^{293} + A \cdot (T - 293) \quad (2)$$

To determine the pore diffusion coefficient for the cereal grain during convective drying S. Kang *et al*. [8] used the analytical solution of diffusion differential equation for the infinite cylinder:

$$\frac{\overline{w}^c - w_p}{w_n^c - w_p} = \sum_{n=1}^{\infty} B_n \cdot e^{-A_n^2 \cdot Fo} = \sum_{n=1}^{\infty} \frac{4}{m_n^2} \cdot e^{-A_n^2 \cdot Fo} \quad (3)$$

However, all above-mentioned dependencies are correct only for investigated materials and drying methods, namely for definite technological parameters, structures, layer porosity, particles geometrical size, *etc*. It is impossible to use them for determination of pore diffusion coefficient of wheat grain because the difference between experimental and calculated data is great.

Table 1

Main characteristics of "Zolotokolos" wheat grain [9]

ρ_{bulk}, kg/m^3	ρ_{add}, kg/m^3	Weight of 1000 grains, G_{1000}, kg	ε, m^3/m^3	k	$d_e \cdot 10^3$, m	a, m^2/m^3
751.81	1181.3	$4.61 \cdot 10^{-3}$	0.3636	0.8	1.56	934.67

Table 2

Geometrical characteristics of "Zolotokolos" wheat grain [9]

Averaged linear sizes, m			Area of grain external surface, $S_{gr} \cdot 10^3$, m	Grain volume, $V_{gr} \cdot 10^5$, m^3
Length, $l \cdot 10^3$	Thickness, $a \cdot 10^3$	Width, $b \cdot 10^3$		
7.01	3.148	3.876	7.32	4.54

The aim of this work is to study diffusion mass transfer during grain FD of "Zolotokolos" wheat and to determine diffusion coefficient depending on heat agent temperature.

2. Experimental

2.1. Investigation objects

The grain of "Zolotokolos" wheat was chosen as an investigation object. This sort of wheat is widely used for alcohol production. Its main characteristics are represented in Tables 1 and 2.

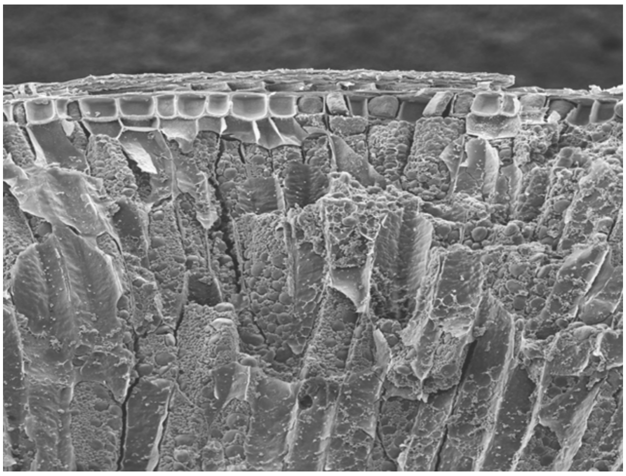

Fig. 1. Cross-section of wheat grain (photo from SuperCoolpics.com)

According to the classification of solid materials subjected to drying, the grain is a colloid capillary-porous body [4]. Internal parts of the grain are bounded by a great number of micro- and macrocapillaries through which the moisture is diffused toward external aleurone layer and then transferred to the heat agent as a steam. The aleurone layer consists of thick-walled cells through which the moisture is leaked. The internal part of the grain consists of thin-walled cells and its weight is much greater compared with that of aleurone layer (Fig. 1). Taking into account that the grain is a live biological system sensitive to the temperature change, it is necessary to dry it under the conditions ensuring high quality of the end product.

2.2. Investigation Procedure

The investigations were carried out using laboratory plant and procedure described in [10]. The process parameters are: layer height H = 80 mm, range of heat agent temperatures 313–353 K, filtration speed is υ=1,38 m/s. The coefficient of moisture pore diffusion mass transfer is the function of two parameters: moisture gradient and temperature gradient. Under the same difference of internal moisture content the temperature factor is a decisive one while determining the pore diffusion coefficient D_w. It is known that FD method combines two phenomena:

1. Moisture removal from aleurone layer external surface that increases internal gradient of moisture content.
2. Possibility of using heat agent at the temperature determined by biological nature of the grain.

We determined experimentally the change of grain moisture content at different temperatures and dynamics of grain layer heating during FD to determine its average temperature.

3. Results and Discussion

The experimental results of FD kinetics are represented in Fig. 2 and dynamics of grain layer heating (H = 80 mm) at 333 K (heat agent temperature) during FD. The average temperature of wheat grain was determined in accordance with heat balance equation.

The analysis of obtained results shows that kinetic curve of wheat grain drying is characterized by only second period of drying. The increase of heat agent temperature decreases drying time (Fig. 2). The reason is the increase of grain layer temperature and coefficient of pore diffusion, correspondingly.

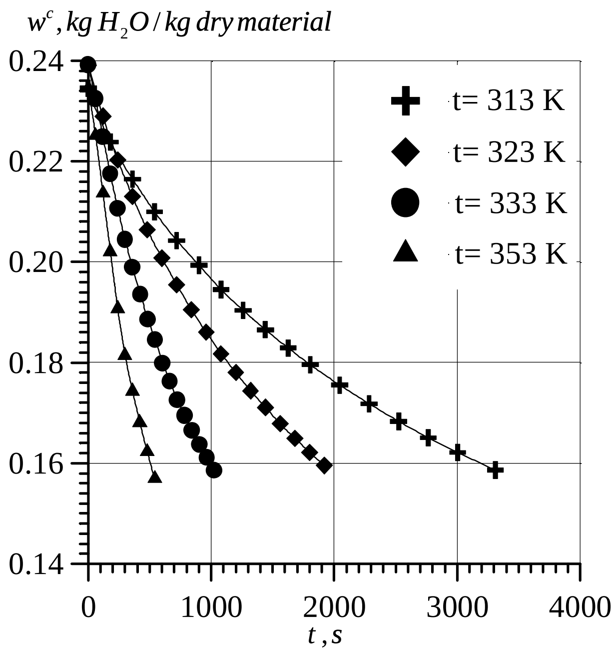

Fig. 2. FD kinetics of "Zolotokolos" wheat grain at different temperatures of heat agent

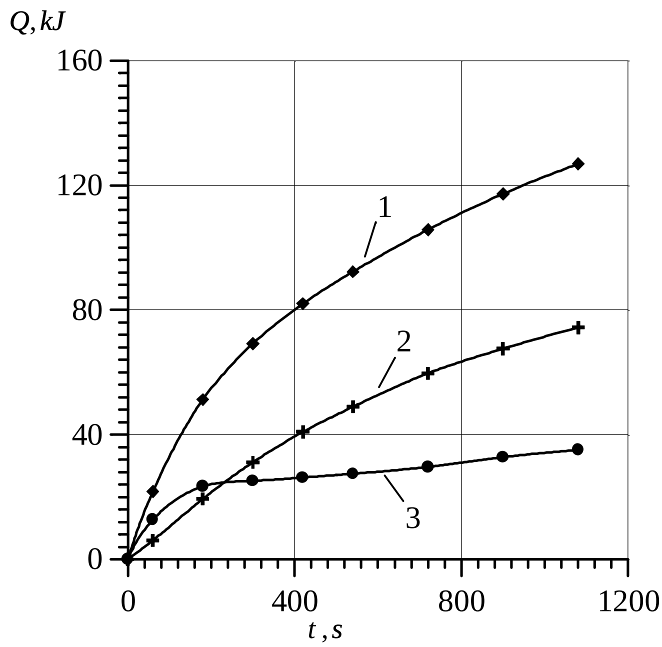

Fig. 3. Heat consumption during FD of grain layer: for heating of the heat agent (1); for moisture evaporation (2) and for heating of the grain layer (3)

The method of D_w determination is based on mathematical solution of pore diffusion differential equation. To describe moisture diffusion in the grain we assume the following positions in view of wheat grain complex form:

– the grain has a cylindrical form of finite size;

– every grain in the layer is uniformly washed by heat agent;

– moisture content on the grain surface corresponds to that in heat agent;

– initial moisture is uniformly distributed in the grain volume.

Taking into account all above-mentioned the task was reduced to the boundary conditions of the first order for the cylinder of finite size, when moisture content is a function of three variables (time, radius and coordinate *z*). The diffusion equation has the form [11]:

$$\frac{\partial w^c}{\partial t} = D_w \cdot \left(\frac{\partial^2 w^c}{\partial r^2} + \frac{1}{r} \cdot \frac{\partial w^c}{\partial r} + \frac{\partial^2 w^c}{\partial z^2} \right) \tag{4}$$

According to corresponding initial and boundary conditions:

$$\begin{cases} w^c(r, z, 0) = w_i^c \\ w^c(r, \pm l, t) = w_{eq}^c, \; w^c(R, z, t) = w_{eq}^c \end{cases} \tag{5}$$

where D_w – coefficient of pore diffusion, m^2/s; *r* and *R* – running radius and grain radius, respectively, m; *l* – grain length, m; *t* – time, s; w^c, w^c_{eq}, w^c_i – running, equilibrium and initial moisture content, respectively, kg H_2O/kg dry material.

It is impossible to find the moisture content along grain radius and length, thereby we determine the average value of moisture content in the grain volume according to Eq. (6):

$$\overline{w}^c = \frac{1}{V} \cdot \int_V w^c \cdot dV \tag{6}$$

Then taking into account the similarity of heat and mass transfer the solution of Eq. (4) with boundary conditions (5) and average value (6) is [11]:

$$\frac{\overline{w}^c - w_p}{w_n^c - w_p} = \sum_{n=1}^{\infty} \sum_{m=1}^{\infty} A_n \cdot A_m \cdot J_0 \cdot \left(m_n \cdot \frac{r}{R} \right) \cos m_m \cdot \frac{z}{l} \cdot e^{-(m_n^2 + m_m^2 \cdot K_l^2) \cdot Fo} \tag{7}$$

where $A_n = \dfrac{2}{m_n \cdot J_1 \cdot (m_n)}$, $m_n = (2 \cdot n - 1) \cdot \dfrac{p}{2}$ – roots of the first kind Bessel function of zero-order; $A_m = (-1)^{m+1} \cdot \dfrac{2}{m_m}$; $m_m = (2 \cdot m - 1) \cdot \dfrac{p}{2}$; $K_l = \dfrac{R}{l}$; $Fo = D_w \cdot t / R^2$ – the Fourier number.

Table 3

D_w values at different temperatures of heat agents

t, K	293	313	323	333	353
$D_w \cdot 10^{10}$, m²/s	0.4	2.1	3.76	7.41	14.2

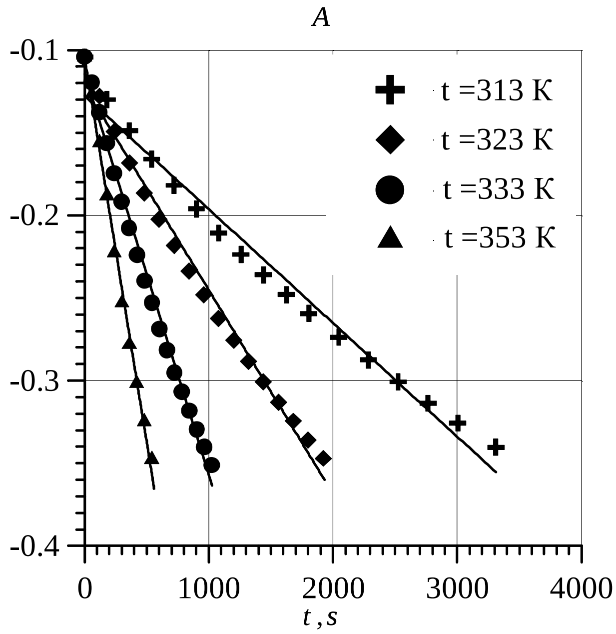

Fig. 4. Dependence of *A* vale on FD time for the wheat grain

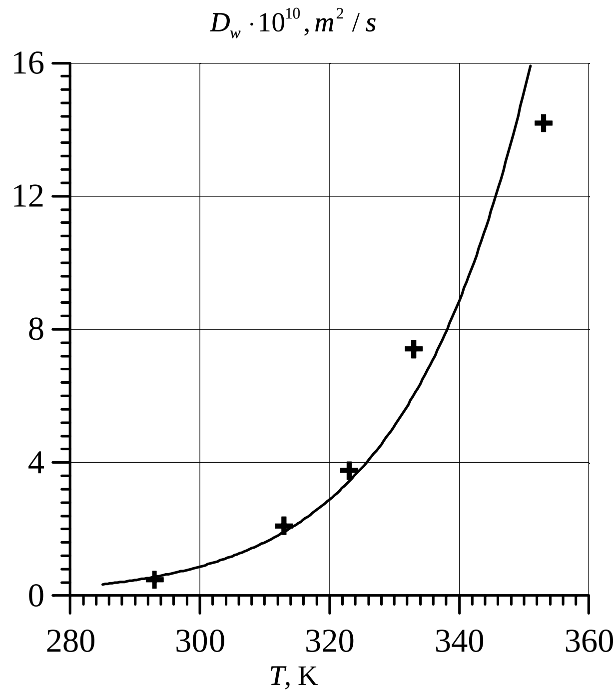

Fig. 5. Dependence of D_w on temperature for the wheat grain

Thus Eq. (7) has the form:

$$\frac{\overline{w}^c - w_p}{w_n^c - w_p} = \sum_{n=1}^{\infty}\sum_{m=1}^{\infty} B_n \cdot B_m \cdot \exp\left[-\left(m_n^2 + m_m^2 \cdot K_l^2\right) \cdot Fo\right] \quad (8)$$

where $B_n = 4/m_n^2$, $B_m = 2/m_m^2$.

We introduce the following designations: $\frac{\overline{w}^c - w_p}{w_n^c - w_p} = \Delta w^c$ and $\frac{\ln\left(\Delta w^c / \left(B_n \cdot B_m\right)\right)}{m_n^2 + m_m^2 \cdot K_l^2} = A$.

To simplify the calculations we use only the first roots of the characteristic equation. Taking the logarithm of Eq. (8) with mentioned simplifications we obtain the graphical dependence $A = f(t)$ (Fig. 4).

Analyzing Fig. 4 we see that experimental data may be approximated by a straight line and the coefficient of pore diffusion D_w is determined according to the slope ratio, *i.e.*:

$$D_w = tga \cdot R^2 \quad (9)$$

Table 3 represents D_w values depending on the heat agent temperature.

The increase of heat agent temperature increases the value of D_w (Table 3, Fig. 5). This fact is not in contradiction with the physical essence of the process but in agreement with literature data [8, 12]. To use in practice the obtained experimental data for other temperatures we determined the coefficient of pore diffusion depending on temperature and approximated them by power dependence.

Then the calculated dependence of D_w within the temperature range 313 ≤ *T* ≤ 353 K may be represented as follows:

$$D_w^t = D_w^{293} + 0.39 \cdot 10^{-12} \cdot (t - 293)^2 \quad (10)$$

Comparing Eq. (10) and analytical dependencies given in the literature we assume that the temperature influence is greater for the biological object than that for other ones, especially of mineral nature.

4. Conclusions

We investigated the kinetics of "Zolotokolos" wheat grain filtration drying at different temperatures and determined that drying proceeds in the second period. We analytically described the pore diffusion mass transfer during grain filtration drying based on the solution of pore diffusion equation. The dependence of pore diffusion coefficient on temperature was investigated as well. The calculated values are in good agreement with experimental data within 313–353 K and maximum relative error is less than 9.3 %.

References

[1] Kyrpa M.: Naukovi Praci Odessa Nats. Acad. Kharch. Techn., 2009, **38**, 147.
[2] Mujumdar A. and Kudre T.: Progress in Drying Technologies, v. 7. Marcell Dekker, NY 2001.
[3] Burdo O., Terziev S., Yarovoi I. and Borsh A.: Problemele Energeticii Regionale, 2012, **18**, 36.
[4] Cniegkin Y., Pazyuk V., Petrova Zh. and Chalaev D.: Teplonasosna Zernosusharka dlya Nasinnevogo Zerna. Poligraf-Servis, Kyiv 2012.
[5] Atamanyuk V: Doctoral thesis, Lviv Polytechnic Nat. Univ., Lviv 2007.
[6] Mosyuk M.: PhD thesis, Lviv Polytechnic Nat. Univ., Lviv 2012.
[7] Barna I., Gumnitsky Ya. and Atamanyuk V.: Chem. & Chem. Techn., 2013, **7**, 461.
[8] Kang S. and Delwiche R.: Trans. Am. Soc. Agr. Eng., 2000, **43**, 1653.
[9] Atamanyuk V., Matkivska I. and Mosyuk M.: Zbirnyk Nauk. Prats Odessa Nats. Acad. Kharch. Techn, 2013, **43**, 10.
[10] Atamanyuk V. and Gumnitsky Ya.: Prom. Teplotechn., 2009, **31**, 36.
[11] Lykov A.: Teoria Teploprovodnosti. Vysshaya schkola, Moskwa 1967.
[12] Rudobashta S. and Nuriev N.: Trudy I Megdunar. Nauchn.-Prakt. Konf. "Sovremennye Energosberegaushie Teplovye Technologii", Moskwa 2002, **4**, 56.

КІНЕТИКА ДИФУЗІЙНОГО МАСОПЕРЕНЕСЕННЯ ПІД ЧАС ФІЛЬТРАЦІЙНОГО ВИСУШУВАННЯ ЗЕРНОВИХ МАТЕРІАЛІВ

Анотація. *В роботі представлені теоретичні та експериментальні дослідження з визначення коефіцієнта внутрішньої дифузії вологи із зерна пшениці під час фільтраційного сушіння. Для знаходження коефіцієнта внутрішньої дифузії використана модель, що базується на розв'язку диференційного рівняння внутрішньої дифузії за граничних умов першого роду. Отримана розрахункова залежність для визначення коефіцієнтів внутрішньої дифузії від температури теплового агенту.*

Ключові слова: *коефіцієнт внутрішньої дифузії, кінетика висушування, вологовміст, зерно пшениці.*