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DIFFUSIVE MASS TRANSFER DURING DRYING OF GRINDED SUNFLOWER STALKS

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Abstract. Diffusive mass transfer has been studied during drying of grinded sunflower stalks to produce fuel briquettes. Theoretical aspects of diffusive processes during filtration drying have been analyzed. The process of diffusive mass transfer during drying of grinded sunflower stalks particles of prismatic shape has been mathematically described. The temperature effect on effective diffusion coefficient has been examined.

Keywords: grinded sunflower stalks, diffusive mass transfer, filtration drying, prism-shaped particles, effective diffusion coefficient.

1. Introduction

In terms of energy and economic crisis, to develop heat energy of Ukraine, the usage of alternative fuels made from plant materials is a prospective direction. Rough-stalked agricultural wastes form a significant part of mentioned materials. The technology of solid fuel production from this type of material provides stages of preliminary grinding and drying to humidity of 4–12 % favorable for sustainable briquetting and quality characteristics of received briquettes. The share of costs for drying is significant in the manufacturing cost of fuel because modern dryers used now to produce solid biofuels are energy intensive, large and require the installation of treatment equipment [1-3]. All these facts correspondingly increase the cost of the finished product. Therefore, to implement the process of drying the rough-stalked grinded biomass we propose the filtration method that can reduce power inputs of solid biofuel production.

Filtration drying of dispersed materials, in particular grinded rough-stalked matter, is a complex process involving mass and heat transfer. During filtration drying the moisture transfer is defined by regularities of both external and pore diffusion. Since about fifteen types of mass and heat transfer participate in pore diffusion process, the latter one is more complicated and prolonged in comparison with external diffusion process [4, 5].

On the basis of thorough review of works on the theory of drying, S. Rudobashta [5, 6] analyzed differential equations to describe pore-diffusion processes, summarized the research results and suggested differential equations to describe the internal mass transfer in polymer granules in the following form:

$$\frac{du}{dt} = div(D_e(u,t) \cdot grad\ u),\ 0 < x < R,\ t > 0$$

and dependence of effective diffusion coefficient on moisture content $D_e = f(u)_t$ is approximated according to

$$D_e = D_0 \cdot \exp\left[-bu - \left(E^*_{D_0} \cdot (1 - du) \big/ \left(R^* \cdot T\right)\right)\right].$$

S. Mishchenko *et al.* [7] present the investigations concerning pore-diffusion processes in colloidal capillary-porous materials and propose the mathematical model of moisture transfer, the dependence $a_m = x^2 \cdot Fo_{2\max} / t_{2\max}$ to calculate the diffusion coefficient and apparatus for its measurement. The authors in [8, 9] propose the expression to calculate the diffusion coefficient at filtration drying of slag gravel ball-shaped granules

$$D^t_w = D^{293}_w + 2.5 \cdot 10^{-10} \cdot (T - 293)$$

and wheat grain (particles of cylindrical shape)

$$D_w = D^{293}_w + 0.3 \cdot 10^{-13} \cdot \left(T - 293\right)^2 \cdot \left(w^c\right)^{-1.8}.$$

These dependencies are valid only for investigated materials which are characterized by internal structure of the particles with their porosity, sizes and shape. Therefore they cannot be used for calculations of pore diffusion coefficient at filtration drying of grinded sunflower stalks because of considerable difference between experimental and calculated results. The diffusion process occurring during rough-stalked raw materials drying by filtration has its own peculiarities and regularities provided by complex structure of the materials, interaction between their skeleton and water, shape and sizes of the pores, capillaries and particles.

2. Experimental

2.1. Objects of Investigations

Sunflower stalks consist of materials different by their structure. As a result of stalks grinding the particles with fibrous structure are formed from external tissue of the stalk (epidermis), cortex (collenchyma and chlorenchyma), sclerenchyma, parenchyma, primary and secondary phloem and xylem, interfascicular cambium. The particles have a prismatic shape with averaged size of 1.37×1.91×7.14 mm. Actually, each particle may be examined as a system formed by a great number of cells with intracellular space. Cell wall together with plasma membrane form semipermeable confined space of the cell containing liquid. The intracellular space is also filled by liquid. The initial average moisture content of the investigated sunflower stalks is 60 %.

Fibers of sunflower stalks are formed from cell walls, the main compounds of which are biopolymers. Cellulose (glucose polymer) forms wall skeleton; hemicellulose (polymer of glucose and xylose) is a part of cell wall and is present inside the cell; lignin (polymer of aromatic alcohols) provides walls with necessary mechanical strength and hydrophobic properties. Cellulose fibers are bound by hemicellulose bridges and form cellulose-hemicellulose network surrounded by lignin matrix [10]. The stalk composition (%) is: cellulose – 41.8; hemicellulose – 21.3; lignin – 20.1 [11]. Cellulose ($(C_6H_{10}O_5)_n$, where n = 6000–14000) is a linear stereoblock natural polysaccharide composed of D-glucopyranose anhydrides. Hemicellulose also belongs to polysaccharides (polymerization degree n = 100–200), particularly pentozanes $(C_5H_8O_4)_n$ and hexozanes. Lignin is situated inside the cell walls and intracellular space. It binds cellulose and provides the stalks with strength and hardness. The high concentration of above-mentioned compounds defines high calorific power of biofuel made from plant raw material.

2.2. Investigation Procedure

The experiments were carried out at the laboratory plant according to the procedure described in [4, 12]. To study the diffusion processes occurring during filtration drying of grinded sunflower stalks the layer with the height $H = 40R$ was formed (R – the defining size of prism-shaped particle). A container with a sample was placed into a drying installation. Heat agent with the temperatures of 293, 316, 333, 353 and 373 K was filtered through the sample layer. Heat agent flow rate was constant. The temperature was controlled by RT-0102 thermoregulator (accuracy ±0.5 K). The sample weight was measured using Axis AD3000 electronic scales (accuracy ±0.01 g). The experiments were carried out till the material weight became constant.

3. Results and Discussion

We studied the kinetic peculiarities of grinded sunflower stalks filtration drying at different temperatures of the heat agent. The upper limit is such a temperature, under which spontaneous ignition does not occur. The experimental results are represented in Fig. 1. The kinetic curves are characterized by long period of partial saturation of the heat agent by moisture. This fact indicates the proceeding of pore-diffusion processes in the material particles which define the time of filtration drying.

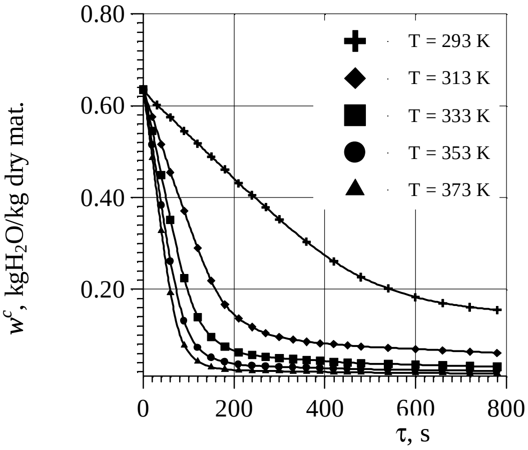

Fig. 1. Kinetics of grinded sunflower stalks drying at different temperatures of heat agent (H = 0.06 m; u_0 = 1.71 m/s)

The increase in heat agent temperature intensifies the drying process. The values of final moisture content (w_f^c) achieved at process time of 600 s are given in Table 1.

Rapid decrease in moisture content with the increase in heat agent temperature indicates the intensification of pore-diffusion processes. Therefore, it is necessary to determine the coefficients of pore diffusion from the particle centre to its surface at different temperatures to predict energy consumption for drying.

Table 1

Moisture content of grinded sunflower stalks at drying time of 600 s

T, K	293	313	333	353	373
w_f^c, kgH$_2$O/kg dry mat.	0.183	0.071	0.035	0.024	0.017

The determination of diffusion coefficients is based on differential equations of pore diffusion with corresponding initial and boundary conditions. Taking into account that particles have a complex structure, we assume the following:

– all particles of grinded sunflower stalks are equal by sizes and have a prismatic shape;

– the heat agent uniformly flows around the particles surface;

– the value of moisture content on the particle surface corresponds to that in the heat agent;

– initial moisture is uniformly distributed through the whole volume of each particle.

During filtration drying the pore diffusion processes inside the sunflower stalks are characterized by several types of mass transfer which have different rates and cannot be divided. Therefore, to analyze diffusive mass transfer occurring inside the particle and on its surface we take into account all types of mass transfer.

So, to solve Eq. (1) we assume the first-type boundary conditions.

For the prism-shaped particles the equation is:

$$\frac{\partial w^{av}(x,y,z,t)}{\partial t}=D_w^*\left[\frac{\partial^2 w^{av}(x,y,z,t)}{\partial x^2}+\frac{\partial^2 w^{av}(x,y,z,t)}{\partial y^2}+\frac{\partial^2 w^{av}(x,y,z,t)}{\partial z^2}\right] \tag{1}$$

where w^{av} – average moisture content of the prism-shaped particle, kgH$_2$O/kg dry mat.; D_w^* – effective diffusion coefficient, m^2/s.

According to Eq. (1) moisture content for the prism-shaped particles is a function of four variables, namely x, y, z coordinates and time t.

To determine the typical size of the particles the origin of coordinates is situated in the particle centre (Fig. 2). Particle length, height and width are denoted as $2R_1$, $2R_2$ and $2R_3$, respectively.

According to above-mentioned assumptions the filtration drying takes place symmetrically relative to the axes. Let us apply the limit (2) on Eq. (1):

$$(t>0;\ -R_1<x<+R_1;\ -R_2<y<+R_2;\ -R_3<z+R_3) \tag{2}$$

At the initial time t_0 the average moisture content w^{av} is the same in the whole volume of the particle and equals to the initial average moisture content w_0^{av}.

Thus, the initial condition is:

$$w^{av}(x,y,z,0)=w_0^{av}=const \tag{3}$$

Due to the heat agent flowing around the particle the average moisture content corresponded to the moisture content of heat agent is set on its surface. As a result, the driving force occurs between the particle surface and its nucleus. Since the average moisture content on the particle surface is equal to that of the heat agent, the boundary conditions are as follows:

$$\begin{aligned} w^{av}(\pm R_1,y,z,t)&=w_{h.a.}^{av}\\ w^{av}(x,\pm R_2,z,t)&=w_{h.a.}^{av}\\ w^{av}(x,y,\pm R_3,t)&=w_{h.a.}^{av} \end{aligned} \tag{4}$$

where $w_{h.a.}^{av}$ – moisture content of the heat agent, kgH$_2$O/kg dry air.

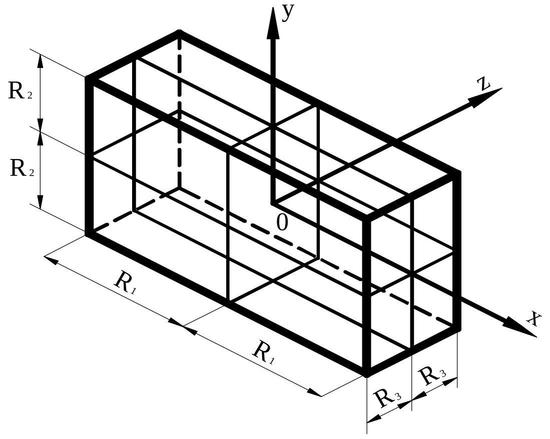

Fig. 2. Schematic drawing of prism-shaped particle

Taking into account limits (2), initial (3) and boundary conditions (4), Eq. (1) may be solved as follows [13]:

$$\frac{w^{av}(x,y,z,t)-w_{h.a.}^{av}}{w_0^{av}-w_{h.a.}^{av}}=\sum_{n=1}^{\infty}\sum_{m=1}^{\infty}\sum_{k=1}^{\infty}A_nA_mA_k\cos\mu_n\frac{x}{R_1}\times \times\cos\mu_m\frac{y}{R_2}\cos\mu_k\frac{z}{R_3}\exp\left[-(\mu_n^2K_1^2+\mu_m^2K_2^2+\mu_k^2K_3^2)Fo\right] \tag{5}$$

where A_n, A_m, A_k – coefficients determined from the dependencies[13]:

$$A_n=(-1)^{n+1}\frac{2}{\mu_n},\quad A_m=(-1)^{m+1}\frac{2}{\mu_m},\quad A_k=(-1)^{k+1}\frac{2}{\mu_k};$$

μ_n, μ_m, μ_k – roots of characteristic equation, which are determined as [13]:

$$\mu_n=(2n-1)\frac{\pi}{2,},\quad \mu_m=(2m-1)\frac{\pi}{2},\quad \mu_k=(2k-1)\frac{\pi}{2}$$

where F_0 – Fourier diffusion coefficient, $Fo=\frac{D_w^*\cdot t}{R^2}$; t – drying time, s; R – generalized size of the particle, m. This value is used taking into account that particle sizes R_1, R_2 and R_3 (according to Fig. 2) are proportional.

Generalized size of the particle is determined from the dependence [13]:

$$\frac{1}{R^2}=\frac{1}{R_1^2}+\frac{1}{R_2^2}+\frac{1}{R_3^2} \tag{6}$$

where $$K_i=\frac{R}{R_i}\qquad (i=1,2,3) \tag{7}$$

On the basis of accepted assumptions Eq. (5) is represented as Eq. [8]:

$$\frac{w^{av}(x,y,z,t)-w^{av}_{h.a}}{w^{av}_{0}-w^{av}_{h.a}}=$$

$$=\sum_{n=1}^{\infty}\sum_{m=1}^{\infty}\sum_{k=1}^{\infty}B_nB_mB_k\exp\left[-(m_n^2K_1^2+m_m^2K_2^2+m_k^2K_3^2)Fo\right] \quad (8)$$

where $B_n=\frac{2}{m_n^2}$, $B_m=\frac{2}{m_m^2}$, $B_k=\frac{2}{m_k^2}$

Under accepted drying conditions and great values of Fourier number we limit ourselves by the first root of the characteristic equation μ_n.

Let us introduce designation:

$$\frac{w^{av}(x,y,z,t)-w^{av}_{h.a}}{w^{av}_{0}-w^{av}_{h.a}}=\Delta w^{av} \quad (9)$$

Taking Eq. (9) into account, Eq. (8) is represented as:

$$\Delta w^{av}=B_nB_mB_k\exp\left[-(m_n^2K_1^2+m_m^2K_2^2+m_k^2K_3^2)Fo\right] \quad (10)$$

or

$$\frac{\Delta w^{av}}{B_nB_mB_k}=\exp\left[-m^2(K_1^2+K_2^2+K_3^2)Fo\right] \quad (11)$$

Taking the logarithm of Eq.(11) we receive:

$$\ln\left(\frac{\Delta w^{av}}{B_nB_mB_k}\right)=-m^2(K_1^2+K_2^2+K_3^2)Fo$$

or

$$-\frac{\ln\left(\Delta w^{av}\right)-\ln\left(B_nB_mB_k\right)}{m^2(K_1^2+K_2^2+K_3^2)}=Fo \quad (12)$$

If we designate

$$A^*=-\frac{\ln\left(\Delta w^{av}\right)-\ln\left(B_nB_mB_k\right)}{m^2(K_1^2+K_2^2+K_3^2)} \quad (13)$$

then Eq. (12) takes a form of:

$$A^*=Fo=\frac{D_w^*\cdot t}{R^2} \quad (14)$$

So, plotting the experimental results as a dependence $A^* = f(\tau)$ we determine the coefficient of moisture diffusion from the prism-shaped particles of the grinded sunflower stalks to the heat agent.

The graphic dependencies have linear character and effective coefficients of pore diffusion D_w^* are determined according to Eq. (15):

$$D_w^*=tga\cdot R^2 \quad (15)$$

The values of D_w^* are represented in Table 2.

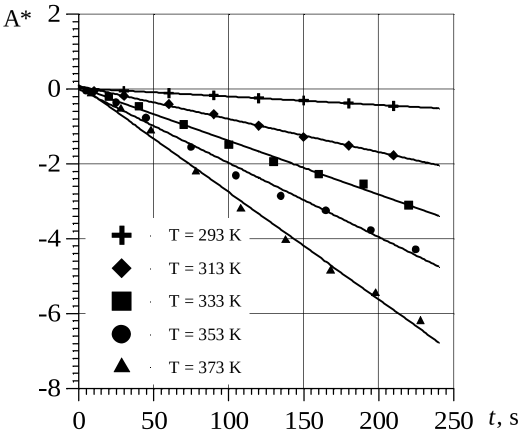

Fig. 3. The value of A^* *vs.* time of particles filtration drying at different temperatures of the heat agent

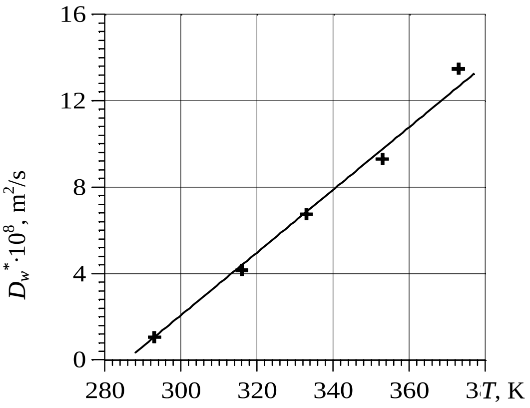

Fig. 4. Effective diffusion coefficient D_w^* *vs.* the heat agent temperature

The increase of heat agent temperature increases the temperature inside the particles and saturation vapor pressure over the liquid surface and thus intensifies the diffusion processes. The graphic dependence $D_w^* = f(\tau)$ is plotted on the basis of results from Table 2 (Fig. 4).

Then the estimated dependence of the effective diffusion coefficient on the heat agent temperature is approximated by Eq. (16):

$$D_w^t=D_w^{293}+1.45\cdot10^{-9}(T-293) \quad (16)$$

Table 2

Dependence of effective diffusion coefficient on heat agent temperature

T, K	293	316	333	353	373
$D_w^*\cdot10^8$, m²/s	1.056	4.156	6.749	9.291	13.474

4. Conclusions

1. Depending on the heat agent temperature the effective diffusion coefficient was determined for the grinded prism-shaped sunflower stalks during filtration drying.

2. The deduced equation allows to calculate theoretically the effective diffusion coefficient for the grinded sunflower stalks within the temperature range of 293–373 K.

3. Maximal relative error between experimental and theoretical values of effective diffusion coefficient (according to the deduced equation) does not exceed 6.3 %, which is acceptable for practical application.

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ДИФУЗІЙНЕ МАСОПЕРЕНЕСЕННЯ ПІД ЧАС ВИСУШУВАННЯ ЧАСТИНОК ПОДРІБНЕНИХ СТЕБЕЛ СОНЯШНИКА

Анотація*. Досліджено дифузійне масоперенесення під час фільтраційного висушування подрібнених стебел соняшника для виробництва паливних брикетів. Проаналізовано теоретичні аспекти дифузійних процесів під час фільтраційного висушування. Математично описано процес дифузійного масоперенесення під час висушування частинок подрібнених стебел соняшника, що мають призматичну форму. Досліджено залежність ефективного коефіцієнта дифузії від температури.*

Ключові слова*: подрібнені стебла соняшника, дифузійне масоперенесення, фільтраційне висушування, частинки призматичної форми, ефективний коефіцієнт дифузії.*