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## ACTIVATION ENERGY AND EFFECTIVE MOISTURE DIFFUSIVITY DETERMINATION IN DRYING OF GRINDED ARTICHOKE STEMS

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By incorporating the advantages and the disadvantages of rotary and fluidized bed dryers, filtration dryer was introduced for grinded artichoke stems drying due to its expected lower energy consumption. The influence of the heat agent temperature (from 313 to 373 K) on kinetics during filtration drying of grinded artichoke stems was investigated. The kinetic curves of grinded artichoke stems was characterized by long period of partial saturation of the heat agent by moisture according to the filtration drying mechanism. Due to the complexity of the filtration drying mechanism, the necessity of the effective moisture diffusivity determination was proved. Effective moisture diffusivity was determined using the Fick's law at five heat agent temperatures (293, 313, 333, 353 and 373 K). Effective moisture diffusivity values at different temperatures  $D_{eff}^T$  were determined to be from  $0.396 \times 10^{-10}$  to  $11.103 \times 10^{-10}$  m<sup>2</sup>/s for grinded artichoke stems: According to Arrhenius equation, the activation energy  $E_a$  and the pre-exponential factor  $D_0$  were calculated to be 24 kJ/mol and  $1.24 \cdot 10^{-6}$  m<sup>2</sup>/s, respectively. Deduced equation allows to calculate theoretically the effective moisture diffusivity for the grinded artichoke stems within temperature range of 293–373 K.

Key words: renewable energy, filtration drying, grinded artichoke stems, heat agent temperature, Arrhenius equation, activation energy.

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## ВИЗНАЧЕННЯ ЕНЕРГІЇ АКТИВАЦІЇ ТА КОЕФІЦІЄНТА ДИФУЗІЇ ВОЛОГИ ПІД ЧАС СУШІННЯ ПОДРІБНЕНИХ СТЕБЕЛ ТОПІНАМБУРА

З урахуванням переваг і недоліків барабаних сушарок і сушарок киплячого шару запропонована фільтраційна сушарка для сушіння стебел топінамбура, яка забезпечуватиме зниження енергоспоживання. Досліджено вплив температури теплоносія (від 313 до 373 К) на кінетику під час фільтраційного висушування подрібнених стебел топінамбура. Кінетичні криві сушіння подрібнених стебел топінамбура характеризуються тривалим періодом часткового насичення теплоносія вологою відповідно до механізму фільтраційного сушіння. З урахуванням складного механізму фільтраційного сушіння доведено необхідність визначення ефективного коефіцієнта дифузії вологи. Коефіцієнт ефективної дифузії вологи визначали за законом Фіка за п'яти температур сушильного агента (293, 313, 333, 353 і 373 К). Визначено, що коефіцієнти ефективної дифузії вологи за різних температур становлять від  $0,396 \times 10^{-10}$  до  $11,103 \times 10^{-10}$  м<sup>2</sup>/с для подрібнених стебел топінамбура. Згідно з рівнянням Арреніуса, енергія активації  $E_a$  і передекспоненціальний фактор  $D_0$  становлять 24 кДж/моль та  $1,24 \cdot 10^{-6}$  м<sup>2</sup>/с відповідно. Запропоноване рівняння дає змогу теоретично обчислити коефіцієнт ефективної дифузії вологи для подрібнених стебел топінамбура в інтервалі температур 293–373 К.

Ключові слова: відновлювані джерела енергії, фільтраційне сушіння, подрібнені стебла топінамбура, температура теплового агента, рівняння Арреніуса, енергія активації.

**Introduction.** Biomass is one of the main sources of renewable energy with rapidly growing trend in the European countries. The most common types of biomass are waste raw materials from crop fields and forests therefore research on the development of the bio-fuel production from this type of biomass has thus been attracting more and more attention. In Ukraine plant biomass from crop fields and forests is the dominant renewable energy source and it is suitable to replace fuels by producing bio-gas, bio-ethanol, bio-charcoal as well as solid bio-fuel [1].

Jerusalem artichoke is an economically important plant with advantages of low input cultivation, high crop yield and wide adaptation to climatic and soil conditions. Tubers of this plant are used as functional food ingredients such as inulin [2], fructose and oligofructose [3] as well as bioactive ingredient sources for pharmaceutical and cosmetic applications [4]. Jerusalem artichoke stems, that are about 1–3 m tall, as lignocellulosic by-products are of interest because they are not currently exploited but they can be successfully used as a raw material for solid bio-fuel production. Biomass pellets have proven to be a more sustainable source of energy in international markets and they have much potential in the future. The use of biomass pellets creates new market opportunities in the agricultural sector, reduces dependence on fossil fuels and cuts greenhouse gas emissions associated with their use [5].

The process of solid bio-fuel manufacturing consists of different energy intensive unit operations and among them drying process consumes a large share. The cost of drying is as high as 30 % of total processing cost in most factories. From the drying process moisture content of grinded artichoke stems should be reduced from about 65–70 % to 4–12 % before pressing and it is one of the key factors determining the profitability and success of the manufacturing process [6]. Therefore, drying must be carried out as economically as possible. Therefore, improving the process and adaption of more efficient systems with innovative equipment in drying will help conserve energy.

**Analysis of recent researches and publications.** There are several types of dryers that are commonly used in industry for drying plant biomass, but the most common are rotary and fluidized bed dryers [7]. Several variations of rotary dryers are common, but the most widely used is the direct rotary dryer in which biomass and the heating agent flow through the dryer in one direction, so the hottest gases come in contact

with the wettest material [7]. The fluidized bed drying was found to be a better choice in terms of drying efficiency. The fluidization is a process in which solids are caused to behave like a fluid by blowing gas upwards through the solid filled column. Rotary and fluidized bed dryers have advantages like high mass and heat transfer rates, uniform quality of drying products, they are suitable for both small and large scale operations but they have disadvantages of heavy emission of dust and as a result large consumption of energy for cyclones [8].

By incorporating the advantages and reducing the disadvantages of rotary and fluidized bed dryers, filtration dryer is introduced which will have a commercial potential due to its expected lower energy consumption. During the filtration drying the heat agent flows down through the channels of the fixed layer formed by particles of grinded biomass that is supported on a perforated belt. The large contact area for heat and mass transfer between the heat agent and the wet material results in high drying rates [9]. Filtration dryers are suitable for removal of external moisture (surface moisture) as well as for removal of internal moisture and indicate that they are particularly useful for drying grinded plant biomass. Modeling the filtration drying process and predicting the drying behavior under different conditions is necessary to have a better understanding of the mechanisms of drying. Moisture diffusivity is an important factor that is considered essential to understand for design, analysis, and optimization of filtration drying process.

During the filtration drying a migration of moisture from solid particles to the surface occurs through several mechanisms and it is difficult to separate individual and in this case the rate of moisture movement is described by an effective moisture diffusivity ( $D_{eff}$ ) [10]. The effective moisture diffusivity depends not only on the physical structure of the material and its moisture content, but also on the drying conditions especially on the heat agent temperature. Therefore, air temperature is an important factor in drying. The dryer efficiency is reduced when the heat agent temperature is higher. The influence of temperature on diffusion processes during the filtration drying of plant biomass has been studied by scientists and expressions for the effective moisture diffusivity calculation were proposed for wheat grain [11], pumpkin [12] and grinded energy willow [13]. These dependencies are valid

only for investigated materials and they cannot be used for calculations of the effective moisture diffusivity at filtration drying of grinded sunflower stems.

Several methods are presented in literature to determine the effective moisture diffusivity: drying method [14], permeability method [15], sorption kinetics method [16], moisture profile method under non-isothermal condition, thermogravimetric method [17]. As it was mentioned, the effective moisture diffusivity depends on the temperature, and an Arrhenius equation is used to calculate it [18]:

$$D_{eff}^T = D_0 \exp \left( - \frac{E_a}{R \cdot T_a} \right), \quad (1)$$

where  $D_0$  is the pre-exponential factor of the Arrhenius equation ( $m^2/s$ );  $E_a$ —the activation energy (kJ/mol);  $R$  — the universal gas constant (8,3143 kJ/(mol·K));  $T_a$  — the absolute air temperature (K).

Linearization of the equation (1) gives:

$$\ln D_{eff}^T = \ln D_0 - \left( \frac{E_a}{R \cdot T_a} \right). \quad (2)$$

According to equation (2), the energy of activation can be calculated by plotting experimental values of  $\ln(D_{eff}^T)$  at different temperatures versus  $(1/T_a)$ .

Investigators have studied numerous researches about the energy of activation on the thin layer drying of various agricultural products, but reliable data on the energy of activation as well as on the effective moisture diffusivity are not available for grinded artichoke stems.

**The aim of the work** was to determine the activation energy for effective moisture diffusivity calculation according to Arrhenius equation in filtration drying of grinded artichoke stems.

**Results of the research.** Grinded artichoke stems (particles from 0,08 to >5,0 mm) were used as a raw material for the drying experiments. The average initial moisture content of the material formed by such particles was

$$w_i = 0,65 \text{ kg } H_2O / \text{kg dry.mat.}$$

To determine the activation energy, grinded artichoke stems samples were experimentally dried over a wide range of temperatures using filtration dryer which involved a drying chamber, vacuum pump, receiver; electronic vacuum gauge, shut-off and regulating valves, electronic flowmeter,

electronic thermostat, heat agent heater and fan as a main units. Samples were formed in drying chamber with duralumin perforated plate as the material layer with the height  $H = 20 \cdot d_e$  ( $d_e$  — the defining size of a round-shaped particle). The drying experiments were carried out at the constant heat agent velocity and constant height of the sample. Heat agent with the temperatures of 293, 316, 333, 353 and 373 K was filtered through the sample layer.

Moisture ratio  $MR$  (dimensionless) was defined as following relation:

$$MR = \frac{w_t - w_e}{w_i - w_e}, \quad (3)$$

where  $w_e$  — equilibrium moisture content of particles (at final conditions)

$$w_e = 0,004 \text{ kg } H_2O / \text{kg dry.mat.}$$

$w_i, w_t$  — initial and transition (at any given time) moisture content of particles,  $\text{kg } H_2O / \text{kg dry. mat.}$

The variation of the moisture ratio  $MR = (w_t - w_e) / (w_i - w_e)$  versus drying time  $t$  at heat agent temperatures of 293, 316, 333, 353, 373 K and constant air velocity  $u_0 = 1,7 \text{ m/s}$  is shown in Fig. 1.

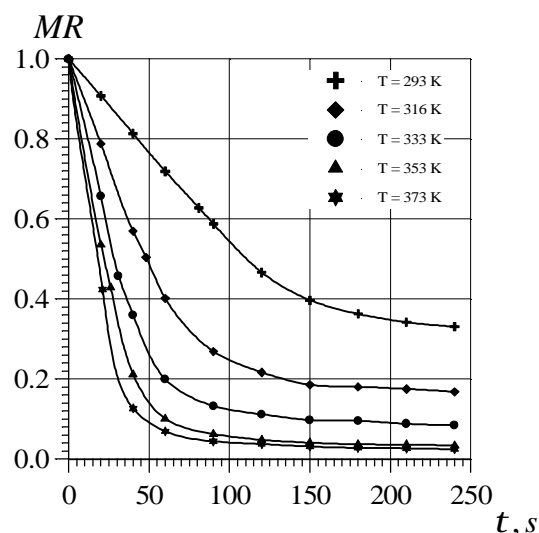


Fig. 1. Moisture ratio  $MR$  vs time  $t$  at various temperatures

The kinetic curves of grinded artichoke stems are characterized by long period of partial saturation of the heat agent by moisture according to the filtration drying mechanism [6]. The experimental values of moisture ratio in period of partial saturation of the heat agent by moisture were plotted as  $\ln MR = f(t)$  (Fig. 2).

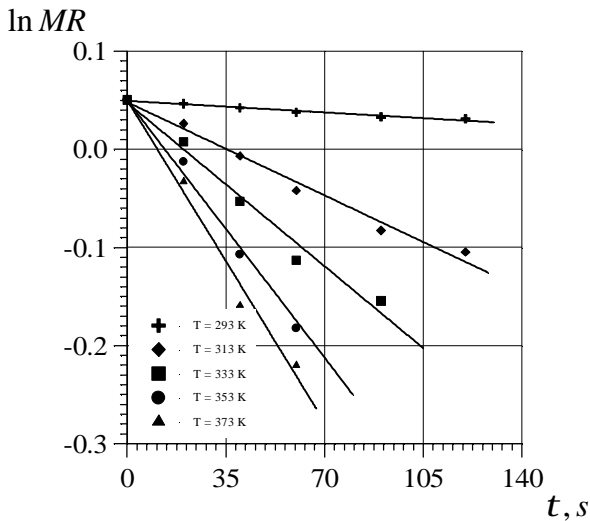


Fig. 2. Natural logarithm of the moisture ratio  $\ln MR$  vs time  $t$ , (for period of partial saturation of the heat agent by moisture)

Straight lines with a slope  $k_0 = tg a$  were obtained and the effective moisture diffusivity values at different temperatures  $D_{eff}^T$  were determined as [10]:

$$D_{eff}^T = \frac{k_0 \cdot R^2}{p^2}, \quad (4)$$

where  $R$  is a radius of the round-shaped particle,  $m$ .

Effective moisture diffusivity values at different temperatures  $D_{eff}^T$  were determined to be:  $D_{eff}^{293} = 0.396 \cdot 10^{-10}$ ,  $D_{eff}^{313} = 3.211 \cdot 10^{-10}$ ,  $D_{eff}^{333} = 5.641 \cdot 10^{-10}$ ,  $D_{eff}^{353} = 8.872 \cdot 10^{-10}$ ,  $D_{eff}^{373} = 11.103 \cdot 10^{-10}$ . Results postulated that  $D_{eff}$  increases when the temperature rises.

The energy of activation was calculated by using an Arrhenius type equation. For this purpose according to equation (2) experimental values of  $\ln(D_{eff}^T)$  at different temperatures were plotted versus  $1/T_a$  (Fig. 3).

The result shows the linear relationships between  $\ln(D_{eff}^T)$  and  $1/T$ , indicating an Arrhenius-type relationship between the effective moisture diffusivity and the temperature. The activation energy  $E_a$  was determined from the plot of  $\ln(D_{eff}^T)$  versus  $1/T$  as:

$$E_a = k_1 \cdot R, \quad (5)$$

where  $k_1$  is the slope,  $k_1 = tg a$ .

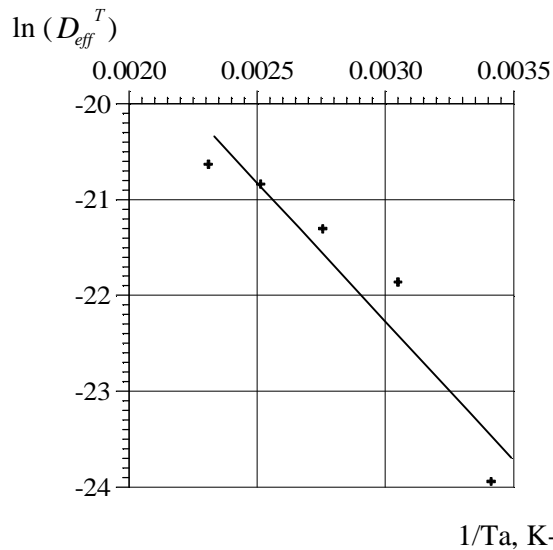


Fig. 3. The logarithm of the effective moisture diffusivity  $\ln(D_{eff}^T)$  as a function of reciprocal of the absolute temperature  $1/T_a$

The intercept equals  $\ln(D_0)$  from which the pre-exponential factor  $D_0$  was calculated. Obtained values are presented in Table.

#### The activation energy $E_a$ and pre-exponential factor $D_0$ values for Arrhenius equation

$k_1 = tg a = \frac{E_a}{R}$	$R$ , J/mol· K	$E_a$ , J/mol	$\ln D_0$	$D_0$ , $m^2/s$
2890	8,3143	24000	-13,6	$1,24 \cdot 10^{-6}$

Taking into account the activation energy  $E_a$  and pre-exponential factor  $D_0$  values, equation (1) can be represented as:

$$D_{eff}^T = 1,24 \cdot 10^{-6} \exp\left(-\frac{24000}{83143 \cdot T_a}\right). \quad (6)$$

The deduced equation (6) allows to calculate theoretically the effective moisture diffusivity for the grinded artichoke stems within temperature range of 293–373 K.

#### Conclusion

The influence of the heat agent temperature (from 313 to 373 K) on kinetics in filtration drying of grinded artichoke stems was investigated. The activation energy  $E_a$  and the pre-exponential factor  $D_0$  for drying of grinded artichoke stems were calculated to be 24 kJ/mol and  $24 \cdot 10^{-6} m^2/s$ , respectively. Equation (6) was deduced which allows to calculate theoretically the effective moisture diffusivity for the grinded artichoke stems within temperature range of 293–373 K.

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