Vol. 2, No. 1, 2019

D. P. Kindzera[1], V. M. Atamanyuk[1], M. P. Pelekh[2], R. R. Hosovskyi[1]
[1] Lviv Polytechnic National University,
Department of Chemical Engineering
[2] Hetman Petro Sahaidachnyi National Army Academy,
kindzera74@ukr. net

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

https://doi.org/10.23939/ctas2019.01.110

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 artishoke 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 × 10–10 to 11.103 × 10–10 m^2/s for grinded artichoke stems: According to Arrhenius equation, the activation energy Ea and the pre-exponential factor D_o were calculated to be 24 kJ/mol and 1.24.10^{-6} m^2/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 artishoke stems, heat agent temperature, Arrhenius equation, activation energy.

Д. П. Кіндзера[1], В. М. Атаманюк[1], М. П. Пелех[2], Р. Р. Госовський[1]
[1] Національний університет "Львівська політехніка",
кафедра хімічної інженерії
[2] Національна академія сухопутних військ імені гетьмана Петра Сагайдачного,
kindzera74@ukr. net

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

З урахуванням переваг і недоліків барабанних 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 × 10^{-10} до 11,103 × 10^{-10} м^2/с для подрібнених стебел топінамбура. Згідно з рівнянням Арреніуса, енергія активації Еа і передекспоненціальний фактор Do становлять 24 кДж/моль та 1,24,10^{-6} м^2/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 агенту, 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. Tubes 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, thermo-gravimetric method [17]. As it was mentioned, the effective moisture diffusivity depends on the temperature, and an Arrhenius equationis used to calculate it [18]:

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

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:

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

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

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

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:

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

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

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

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

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 $u_0 = 1{,}7\ m/s$ is shown in Fig. 1.

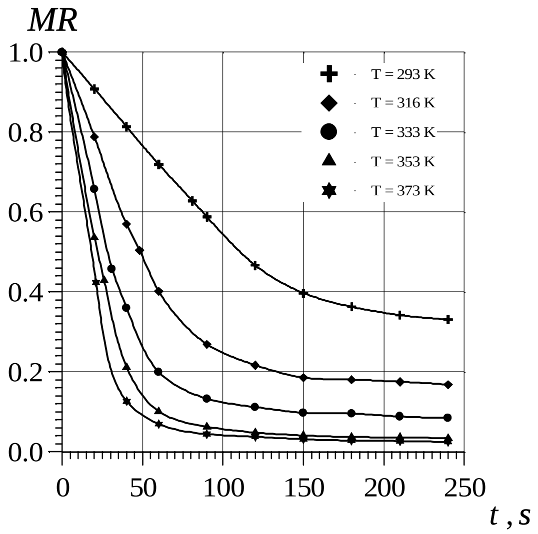

Fig. 1. Moisture ratio MR vs time t at various temperatures

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).

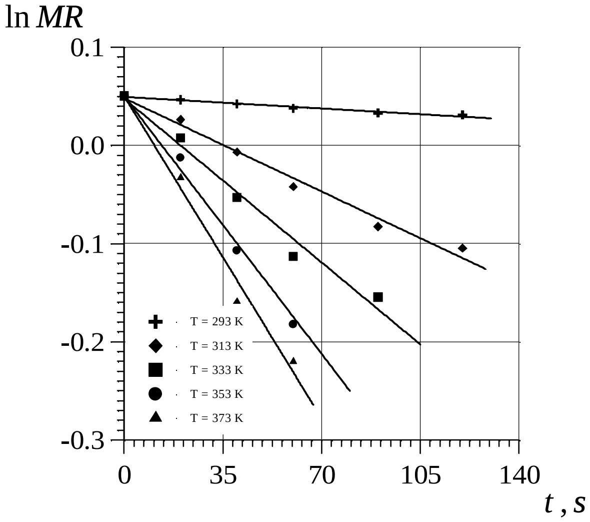

Fig. 2. Natural logarithm of the moisture ratio $\ln MR$ vs time t, (for period of partial saturation of the heat agent by moisture)

Straight lines with a slope $k_0 = tga$ 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 Deff 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 *Ea* 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, $k_1 = tga$.

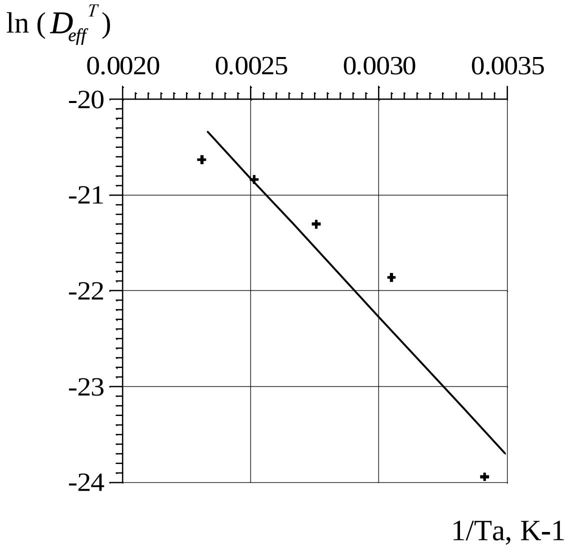

Fig. 3. The logarithm of the effective moisture diffusivity ln ($D_{eff}{}^T$) as a function of reciprocal of the absolute temperature 1/Ta

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

The activation energy *Ea* and pre-exponential factor Dovalues for Arrhenius equation

$k_1 = tga = \frac{E_a}{R}$	R, J/mol·K	Ea, J/mol	lnD$_o$	D$_o$, m^2/s
2890	8,3143	24000	–13,6	$1{,}24 \cdot 10^{-6}$

Taking into account the activation energy *Ea* and pre-exponential factor Do 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.

Conclution

The influence of the heat agent temperature (from 313 to 373 K) on kinetics in filtration drying of grinded artishoke stems was investigated. The activation energy E_a and the pre-exponential factor D_o for drying of grinded artichoke stems were calculated to be 24 kJ/mol1 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.

References

1. Bridgwater A. V., Meier D., Radlein D., (1999) An overview of fast pyrolysis of biomass, ***Org. Geochem***. – 30 1479–1493, http://dx. doi. org/10.1016/S0146-6380(99)00120-5**.**

2. Nair K. K., Kharb S., Thompkinson D. K. (2010) Inulin dietary fiber with functional and health attributes. A review ***Food Rev. Int.***, 26, pp. 189–203.

3. Roberfroid M. B. (2002) Functional food: concepts and application to inulin and oligofructose ***Br. J. Nutr.***, 87, pp. S139–S143.

4. Xiao Z. J., Zhu D. H., Wang X. H., Zhang M. D. (2013) Study on extraction process of inulin from Helianthus tuberosus ***Mod. Food Sci. Technol***., 29, p. 02.

5. Karkania V., Fanara E., Zabaniotou A. (2012) Review of sustainable biomass pellets production – A study for agricultural residues pellets'market in Greece Review Article / ***Renewable and Sustainable Energy Reviews***, Vol. 16, Issue 3, P. 1426–1436.

6. Gosovskiy R., Kindzera D., Atamanyuk V. (2016). Diffusive mass transfer during drying of grinded sunflower stalks. ***Chemistry&Chemical Technology***. Vol. 10, No. 4: P. 459–463.

7. Kindzera D., Atamanyuk V. and Hosovskyi R. (2015 Acad) Determination of optimum parameters of drying of crushed sunflower stems for the production of fuel briquettes. ***Visnyk Odesa Nats.***, 47(2), 194–198.

8. Snezhkin Yu., Korinchuk D., Vorobiov L. and Kharin O. (2006) ***Prom. Teplotechn.***, 28, 41.

9. Atamanyuk V. and Gumnytskyi Ya. (2013) ***Naukovi Osnovy Filtracijnogo Sushinnya Dispersnykh Materialiv***. P. 235 Lviv: Vyd-vo Lviv. Polytech.

10. Госовський Р. Р., Кіндзера Д. П., Атаманюк В. М. (2017) Внутрішньодифузійне масоперенесення під час фільтраційного сушіння подрібненої паренхімної тканини стебел соняшника *Науковий вісник НЛТУ України*, Т. 27, № 6. С. 112–116.

11. Атаманюк В. М., Матківська І. Я., Барна І. Р. (2015) Сушіння зерна пшениці фільтраційним методом *Вісник Нац. ун-ту "Львівська політехніка". Хімія, технологія речовин та їх застосування*. № 812. С. 302–307.

12. Atamanyuk V., Huzova I., Gnativ Z., Mykychak B. (2016) Selection of optimal method of forming a layer of candied fruits during filtration drying *Східно-Європейський журнал передових технологій*. Vol. 5, No. 11(83). P. 10–16.

13. Атаманюк В. М. Гумницький Я. М., Мосюк М. І. (2011) Кінетика внутрішньодифузійного процесу сушіння подрібненої "енергетичної" верби. *Науковий вісник НЛТУ України: збірник науково-технічних праць*. Львів: РВВ НЛТУ України. Вип. 21.14. С. 95−101.

14. Celma A. R., López-Rodríguez F., Blázquez F. C. (2009) Experimental modelling of infrared drying of industrial grape by-products, ***Food Bioprod. Process***. 87 247–253, http://dx. doi. org/10.1016/j. fbp.2008.10.005.

15. Civan F., Rai C. S., Sondergeld C. H., (2011) Shale-gas permeability and diffusivity inferred by improved formulation of relevant retention and transport mechanisms, ***Transp. Porous Media*** 86 925 – 944, http://dx. doi. org/10.1007/s11242-010-9665-x.

16. Wong E. H., Cook J., Dreno M., Chen D.-L., Lai Y.-S. (2015) Characterising Arrhenius moisture diffusivity constants using non-isothermal sorption, ***Microelectron. Reliab***. 55 2331–2335, http://dx. doi. org/10.1016/j. microrel.2015.06.053.

17. Li Z., Kobayashi N. Determination of moisture diffusivity by thermo-gravimetric analysis under non-isothermal condition, ***Dry. Technol***. 23 1331–1342.

18. Aghbashlo M, Kianmehr MH, Samimi-Akhljahani H (2008) Influence of drying conditions on the effective Effective moisture diffusivity, energy of activation and energy consumption during the thin-layer drying of barberries fruit (Berberidaceae). ***Energy Conversion and Management*** 49, 2865–287.