Iranian Journal of Food Sciences and Industries, No. 132, Volume 19, February 2023

Journal of Food Science and Technology (Iran)

Homepage: www.fsct.modares.ir

Scientific Research

Selection and evaluation of thin-layer drying models for describing drying kinetics of garlic slices in an infrared dryer

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ABSTRACT

To improving energy efficiency and increasing quality of dried product, a infrared dryer was constructed that can be used to dry fruits and vegetables. In this study, drying kinetics modeling of garlic in an infrared dryer was investigated. The effect of samples distance from the radiation lamp in three levels of 5, 7.5 and 10 cm and the effect of garlic slices thickness in the in three levels of 3, 6 and 9 mm on the mass transfer rate and effective moisture diffusivity coefficient during the dry process of garlic was investigated. To determine the appropriate kinetics model in the drying process, the drying curves can be analyzed under the defined conditions. Therefore, in this research, to investigate on the drying kinetics of garlic slices, the standard models were fitted to the experimental data. By increasing the distance of the samples from the heat source from 5 to 10 cm, the average drying time of garlic increased from 35.8 minutes to 37.3 minutes. By increasing the thickness of the samples from 3 to 9 mm, the average drying time of garlic increased from 22.7 minutes and 50.9 minutes. The effect of sample distance from infrared heat lamp and sample thickness on changes in effective moisture diffusivity coefficient of garlic was investigated and results showed that this coefficient values were increased with decreasing in distance and increasing samples thickness. By reducing sample distance from the lamp from 10 to 5 cm, it was observed that the effective moisture diffusivity coefficient increased from 2.71×10^{-9} m^2s^{-1} to 3.63×10^{-9} m^2s^{-1}. The average effective moisture diffusivity coefficient of garlic slices for thicknesses of 3, 6, and 9 mm were 0.94×10^{-9} m^2s^{-1}, 2.72×10^{-9} m^2s^{-1}, and 5.54×10^{-9} m^2s^{-1}, respectively. In drying process modeling of garlic, the Midilli model with the highest coefficient of determination and the lowest error, had closer results to the experimental data than the other models.

ARTICLE INFO

Article History:

Received 2022/ 07/ 07
Accepted 2023/ 02/ 02

Keywords:

Drying time,
Effective moisture diffusivity,
Garlic,
Midilli model.

DOI: **10.22034/FSCT.19.132.377**
DOR: **20.1001.1.20088787.1401.19.132.28.1**

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[DOR: 20.1001.1.20088787.1401.19.132.28.1]

[DOI: 10.22034/FSCT.19.132.377]

1. Introduction

garlic (*Allium sativum* L.) is an agricultural product with high nutritional value that is mostly available in the market in early summer. Garlic is rich in natural antioxidants, phenolic compounds and antimicrobial compounds. Garlic, fresh or dried, is used as a flavoring agent in a variety of foods. Dried garlic has a longer shelf life than fresh garlic. Dried garlic is one of the food additives that is very important from the commercial point of view and is prepared in the form of sheets or powder. Garlic, due to its aromatic compounds, is sensitive to heat, so its drying process should be such that the quality of the final product in terms of color, aroma, taste, and ingredients is maintained as much as possible [1, 2]. In a research, Bayat (2006) investigated the effect of different drying conditions with temperatures of 50, 60, and 70 degrees Celsius on the final quality of dried garlic. The drying curves showed that the moisture content of garlic is exponential function with decreasing drying time and more garlic drying is done in the descending stage of the process. The thickness of 3 mm garlic slices in each of the temperature conditions gave the best quality, but it was associated with the longest drying time. According to the results of this research, this thickness can be used in temperature conditions higher than 60 degrees Celsius in order to compensate for the negative effects caused by high temperatures [1]. In another study, Bayat et al. (2016) investigated the physical stability of garlic powder dried by freeze drying and hot air flow methods. The results of drying 2 mm slices of garlic with two methods of freezing and hot air flow have shown that the amount of pyruvate in frozen garlic powder is higher and its density and color changes are significantly lower than the other sample [3]. Peshwafard and Azadmard Demirchi (2020) investigated the effect of different pretreatments before drying garlic on the quality of produced garlic powder. The results of this research showed that the amount of moisture in all treatments did not change significantly during storage. The control sample had the highest amount of discoloration and browning among the samples. Due to the solubility of flavonoids and vitamin C in water, all pretreatments reduced the amount of these compounds in the produced garlic powder [4]. Rasouli and Sidlo (2012) investigated the changes and mathematical modeling of garlic shrinkage during convective drying. In this research, thin layers of garlic were dried at temperatures of 50, 60, and 70 degrees Celsius and thicknesses of 2, 3, and 4 mm in a laboratory hot air dryer with an air speed of 1.5 m/s. The results of examining changes in the percentage of shrinkage during drying at different air temperatures and sheet thicknesses showed that the effect of drying air temperature and sheet thickness on product shrinkage is not significant and shrinkage is only a function of product moisture level [5].

One of the main goals of drying agricultural products is to reduce the moisture content and bring it to an optimal level to achieve the maximum shelf life and reduce waste. Due to the expansion of new science and different drying methods, the use of new methods such as infrared radiation should be studied [6, 7]. In a research, Hosni et al. (2020) investigated the effect of infrared drying on the quality characteristics of sumac fruit. The results of this research showed that infrared drying, in addition to reducing the drying time, is a suitable method for maintaining the chemical properties and color changes of the whole sumac fruit [8]. Raini Moghbli et al. (2021) investigated the process of drying rice paddy with an infrared dryer. The results of this research showed that the studied factors of temperature and humidity have a significant effect on drying time, but none of the two factors of temperature and humidity were significant on the percentage of shell [7]. Yousefi et al. (2019) investigated the kinetics of infrared drying of fruit slices and its modeling with genetic algorithm-artificial neural networks method. The results of this research showed that by increasing the temperature from 50 to 80 degrees Celsius, the drying time decreased by about 60% (increasing the drying speed) [9].

The review of published articles on the drying of agricultural products indicated that there has been no study related to the study of kinetics of mass transfer and the calculation of the effective diffusion coefficient of moisture when drying garlic slices by infrared method; Therefore, the purpose of this research is to investigate the effect of the thickness of garlic slices and the distance of the irradiation lamp from the sample on the mass transfer rate and

[DOR: 20.1001.1.20088787.1401.19.132.28.1]
[DOI: 10.22034/FSCT.19.132.377]

also to model the process with experimental models.

2- Materials and methods

2-1- Drying process

In order to dry the sliced garlic with thicknesses of 3, 6 and 9 mm, an infrared dryer with a power of 250 W was used and the distance of the samples from the surface of the lamp was set at three distances of 5, 7.5 and 10 cm. Weight changes of samples during drying every one minute by digital scale[1] It was recorded with an accuracy of ± 0.01 g, which was placed under the dryer [10]. The reduction of the moisture content of garlic, on a dry basis, was investigated against the drying time and the effect of different drying treatments on it.

2-2- Calculation of humidity ratio

In most researches, the mathematical models governing the drying process of agricultural and food products are based on the moisture ratio[2] (MR) are obtained. The humidity ratio can make the obtained data uniform and more uniform and prevent data scattering. Having the initial moisture content of the product and reducing its weight, the process of moisture and mass transfer during drying of the product is calculated by equation 1 [11].

$$MR = \frac{M_t - M_e}{M_0 - M_e}$$

In this regard, MR: moisture ratio (dimensionless), M_t Moisture content on a dry basis at any time t (grams of water per gram of dry matter), M_0 Initial moisture content on dry basis and $M_{It\ is}$ It is the equilibrium moisture content (grams of water per gram of dry matter). For long drying times, values of $M_{It\ is}$Compared to the values of M_{of}, M_t It is very small; Therefore, the equation of moisture ratio during drying can be simplified as Equation 2, and there is no need to measure the equilibrium moisture to calculate the moisture ratio [12].

$$MR = \frac{M_t}{M_o}$$

2-3- Calculation of the effective penetration coefficient of moisture

Throughout the drying process, diffusion is the dominant phenomenon of moisture transfer from the center of the sample to the surface, so in this study, the mass transfer space was considered as a flat plate (blade) and moisture removal was calculated based on Fick's second law, according to Equation 3 [13].

$$MR = \frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}\exp(-(2n+1)^2\frac{\pi^2 D_{eff} t}{4L^2})$$

In this regard, L is half the thickness of the sample (in meters), n is the number of terms considered from the equation, t is the drying time (s) and D_{eff} Effective penetration coefficient (m^2s^{-1}) Are. Usually, the first term of this series is considered and the above equation is simplified as equation 4 and the effective diffusion coefficient is obtained through this equation and slope calculation.

$$MR = \frac{m_t - m_e}{m_0 - m_e} = \frac{8}{\pi^2}\exp\left[\frac{-\pi^2 D_{eff} t}{4L^2}\right]$$

By taking the natural logarithm of the sides of equation 4, equation 5 is obtained:

$$\ln MR = Ln\frac{8}{\pi^2} + \left(-\frac{\pi^2 D_{eff} t}{4L^2}\right)$$

Then the effective diffusion coefficient of humidity through the slope of the natural logarithm of the humidity ratio of the experimental data (*Ln*MR) was calculated against drying time and using equation 6.

$$Slope = \frac{\pi^2 D_{eff}}{4L^2}$$

In this regard, Slope is the slope of the line.

2-4- Kinetic modeling

The principle of the modeling process is based on having a set of accurate and simple mathematical equations that can describe mass transfer processes with high accuracy. In this study, in order to investigate the kinetics and predict the drying process of garlic, kinetic modeling was done with the help of experimental data and using different experimental models of drying. Wang and Singh, Handson and Pabis, diffusion approximation, Page, Newton, Midilli and logarithmic equations were selected and analyzed to model the drying process of garlic and choose the best kinetic model [14]. In order to model the experimental data of drying

1. Digital balance, LutronGM-300p (Taiwan)
2. Moisture ratio (MR)

and obtain the constants of the models, MATLAB software version R2012a was used.

5-2- Statistical analysis

This research was analyzed in a factorial format based on a completely random design and using SPSS version 21 software. All the tests were performed in three repetitions and Duncan's multi-range test was used at the 95% probability level to compare the average of the observed responses. Excel (2007) program was also used to draw graphs.

3. Results and Discussion

3-1- Investigation of mass transfer kinetics

Among the different processing methods, drying is a process in which the water activity of food is reduced by removing water through the phenomenon of evaporation; But the quality of products that are dried in the traditional way and are significantly affected by changes during production and storage, is lower than the main food item [15]. The results of the variance analysis of the effect of the distance of the samples from the infrared lamp and the thickness of the garlic slices on the drying time of the garlic have been analyzed and displayed in Table 1. As can be seen in this table, the effect of the independent variable of thickness is significant at the 5% level ($P<0.05$), but the effect of the distance variable and their interaction is not significant at the 5% level ($P<0.05$).

Table 1 Results of analysis of variance for drying time parameters of garlic slices during drying by infrared

Sources of changes	Degrees of freedom	Sum of squares	Mean square	P
Distance	2	11.56	5.78	0.915
Thickness	2	3584.89	1792.44	0.000
Distance × Thickness	4	66.22	16.56	0.902
Error	18	1159.33	64.41	
Total	26	4822.00		

The main goal of the drying process of agricultural products is to reduce the moisture content to a safe level to achieve maximum shelf life. Figure 1 shows the effect of the distance of the samples from the infrared lamp and the thickness of the garlic slices on the drying time.

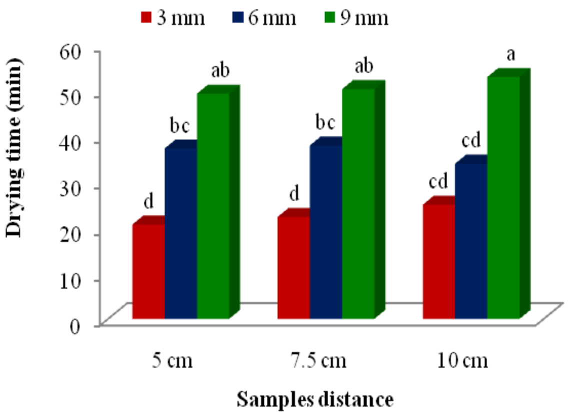

Fig 1 Average of garlic slices drying time at different drying conditions by infrared system

Means with different superscripts differ significantly ($P<0.05$).

As can be seen in this figure, with the increase in the thickness of the slices, the drying time of the samples has increased. The maximum drying time was related to the sample with a thickness of 9 mm, which was located at a distance of 10 cm from the surface of the lamp (53 minutes), and the lowest drying time was related to the sample with a thickness of 3 mm, which was located at a distance of 5 cm from the surface of the lamp. The average drying time for this treatment was 20.7 minutes.

2-3- The results of calculating the effective moisture penetration coefficient

Today, drying of agricultural products is a developed method that by removing part of the moisture leads to the physicochemical stability of the product and also causes the production of different products with new qualitative properties and with different nutritional and economic value. Moisture permeability is the most important feature in drying calculations. Investigating mass transfer kinetics and moisture penetration coefficients can be a useful tool to control drying process conditions and increase product quality. Figure 2 shows the trend of changes in the natural logarithm of the moisture ratio (LnMR) over time at different distances and thickness of 9 mm. Figure 3 also shows the trend of the natural logarithm of the moisture ratio over time for different thicknesses at a distance of

[DOR: 20.1001.1.20088787.1401.19.132.28.1]

[DOI: 10.22034/FSCT.19.132.377]

10 cm. The slope of these lines was used to calculate the effective penetration coefficient. By increasing the thickness of garlic samples from 3 to 6 and from 6 to 9 mm, it was observed that the moisture penetration coefficient from m^{2}s^{-1} $^{9-}$0.94x10 to m^{2}s^{-1} $^{9-}$10x72/2 and from m^{2}s^{-1} $^{9-}$10 x 72.2 to m^{2}s^{-1} $^{9-}$10 x 45.5 increases. This part of the results is in line with the results of Mohammadi et al. These researchers investigated the optimization of the effective moisture diffusion coefficient and the mathematical modeling of the drying kinetics of "Ba" fruit slices and reported that with the increase in thickness at all studied temperatures, the moisture diffusion coefficient had an increasing trend [16]. Yousefi et al. (2019) investigated the kinetics of infrared drying of fruit slices and its modeling. Increasing the temperature from 50 to 80 degrees Celsius increases the effective diffusion coefficient^{9-}8/10 x 10 to^{9-}10 x 1.26 square meters per second [9].

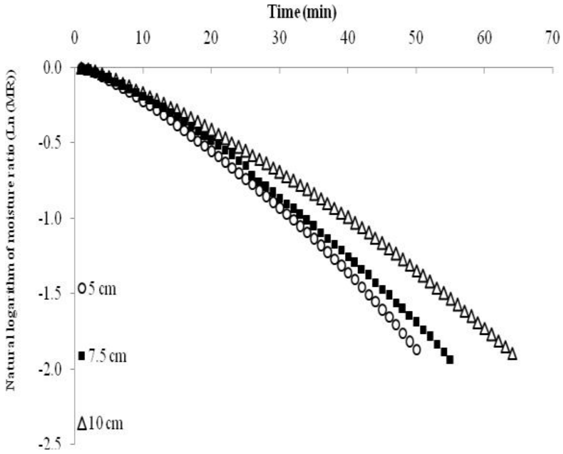

Fig 2 Variations of the natural logarithm of moisture ratio (Ln (MR)) values versus drying time of garlic slices at different samples distance (9 mm thickness).

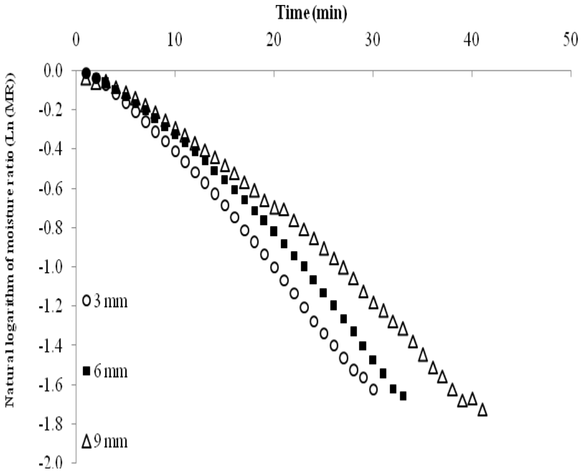

Fig 3 Variations of the natural logarithm of moisture ratio (Ln (MR)) values versus drying time of garlic slices at different samples thickness (10 cm distance).

Different values of the effective diffusion coefficient for research treatments are reported in Table 2. As it can be seen in this table, by reducing the distance of the sample from the lamp, due to the increase in the penetration of infrared rays and the increase in the speed of heat transfer, the effective moisture penetration coefficient has increased. By reducing the distance of the sample from the lamp from 10 to 5 cm, it was observed that the moisture penetration coefficient from m^{2}s^{-1} $^{9-}$10 x 71/2 to m^{2}s^{-1} $^{9-}$10 x 63.3 increased. At a higher temperature (decreasing the distance from the lamp) due to the faster exit of moisture (increasing moisture penetration), the drying process takes place in less time. This decrease in drying time, which occurs as a result of increasing temperature, can be due to the increase in water vapor pressure inside the garlic slices, which increases moisture migration. Hosni et al. (2020) reported that the use of an infrared dryer reduces the drying time of sumac fruit compared to traditional drying methods (shade and sun). Also, the amount of organic acids and vitamin C of sumac fruit in drying in this way is maintained in high amounts compared to the method of drying by microwave dryer [8]. In the results of another research, Hosseini et al. (2021) reported that increasing the power of infrared radiation increases effective penetration coefficients [17].

Table 2 Effective moisture diffusivity values (D_{eff}) of garlic slices at different infrared drying conditions

Distance (cm)	Thickness (mm)	Effective diffusivity (m^2s^{-1})	r
5	3	1.25×10^{-9}	0.995
5	6	3.38×10^{-9}	0.983
5	9	6.27×10^{-9}	0.985
7.5	3	8.41×10^{-10}	0.994
7.5	6	2.49×10^{-9}	0.998
7.5	9	4.99×10^{-9}	0.995
10	3	7.42×10^{-10}	0.998
10	6	2.30×10^{-9}	0.993
10	9	5.08×10^{-9}	0.994

3-3- Choosing the best model to fit the data

To determine the appropriate model in the drying process, drying curves can be analyzed under defined conditions. By calculating the amount of moisture ratio for all the studied treatments during the drying process of garlic (using equation no. 2) and fitting the points obtained by drawing the moisture-time ratio diagrams, by means of Wang and Singh, Henson and Pabis models, diffusion approximation, Page, Newton, Midilli and logarithmic, the results for each model were examined (Table 3). In this table, MR, humidity ratio, t time (min) and n, k, b, l, c and a are constants of the models. The best model should have the highest value of explanation coefficient and minimum error values. The results showed that the best model with the highest fit, according to the mentioned conditions, regarding the garlic drying process, is the Midili model.

Table 3 The statistical parameters obtained in order to verify the fit of each mathematical model to the observed data during the garlic slices drying (distance=10cm and thickness=9 mm)

Model number	Model name	Model equation	Model constants	SSE	r	RMSE
1	Wang and Singh	$MR = 1 + at + bt^2$	a=-0.018 b=8.5e-5	0.0128	0.997	0.0143
2	Henderson and Pabis	$MR = a\exp(-kt)$	a=1.086 k=0.027	0.0435	0.990	0.0262
3	Approximation of diffusion	$MR = a\exp(-kt) + (1-a)\exp(-kbt)$	a=1.192 k=0.024 b=0.942	0.1083	0.976	0.0418
4	Page	$MR = \exp(-kt^n)$	k=0.008 n=1.295	0.0011	0.999	0.0042
5	Newton	$MR = \exp(-kt)$	k=0.0244	0.1085	0.975	0.0411
6	Pony	$MR = a\exp(-kt^n) + bt$	a=1.012 k=0.0105 n=1.222 b=-0.0006	0.0004	0.999	0.0027

7	Logarithmic	$MR = a\exp(-kt) + c$	a=1.41 k=0.016 c=-0.368	0.004 6	0.999	0.0086

The principle of mathematical modeling of the drying process of agricultural and food products is to match mathematical equations to the drying process, which can adequately express the characteristics of the system. Also, by using mathematical models, it is possible to achieve a better understanding of the drying process as a function of various variables by spending less time and money [18]. Considering the lower error resulting from the fitting of the laboratory data with the Midili model and the greater fit of this equation with the laboratory data, during the analysis of garlic drying kinetics, the results of this model are reported in Table 4. In this table, the coefficient of explanation and the coefficients of this model are also presented. Therefore, it is recommended to use this model to check the drying process of garlic slices using the infrared system. In Figure 4, the data obtained by the Midili model is compared with the experimental results. This figure shows the ability of the Midili model to model and predict the drying behavior of garlic. Hosseini et al. (2021) investigated the kinetics and modeling of rosemary drying using infrared. These researchers have recommended the use of the Midili model to predict the drying process of rosemary in an infrared dryer with powers of 200 and 300 watts [17]. In a research, Adabi et al. (2015) investigated the mathematical modeling of the drying process and kinetics of aloe vera gel in a hot air flow dryer with a return air cycle. To fit the standard models of thin layer drying with the experimental data, use the curve fitting environment of MATLAB 2007 software. By comparing error indices and coefficient of determination, it was found that Midili model is the most suitable model for describing laboratory data in this research [11].

Table 4 The constants and coefficients of the accepted model (Midilli)

Distance (cm)	**Thickness (mm)**	**a**	**k**	**n**	**b**	**SSE**	**r**	**RMSE**
5	3	0.994	0.0405	1.298	-0.0021	0.0003	0.999	0.0048
5	6	1.006	0.0125	1.275	-0.0008	0.0003	0.999	0.0027
5	9	1.007	0.0107	1.271	-0.0009	0.0003	0.999	0.0024
7.5	3	0.997	0.0353	1.216	0.0098	0.0002	0.999	0.0026
7.5	6	1.001	0.0181	1.217	0.0025	6.1e-5	0.999	0.0014
7.5	9	1.01	0.0096	1.254	0.0012	0.0004	0.999	0.0028
10	3	1.003	-0.049	0.8606	-0.0753	0.0002	0.999	0.0033
10	6	1.001	-0.051	0.7765	-0.0561	0.0001	0.999	0.0019
10	9	1.012	0.0105	1.222	-0.0006	0.0004	0.999	0.0027

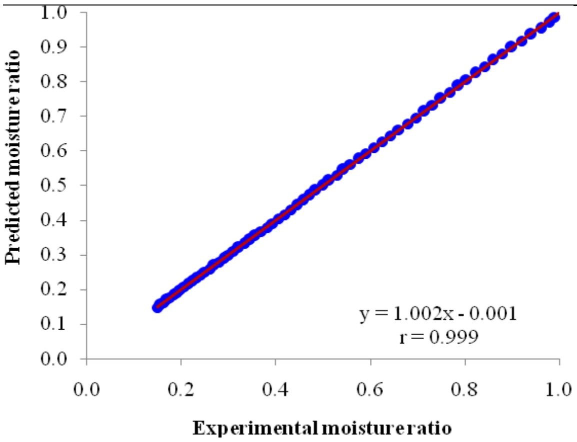

Fig 4 Comparison of fitted data by Midilli model with experimental results (10 cm distance and 9 mm thickness).

4 - Conclusion

In this research, the effect of the sample distance from the infrared lamp and the thickness of the samples on the drying kinetics of garlic slices in an infrared laboratory dryer was studied. The results of this research showed that in order to minimize the drying time and speed up the drying process, the factors of the sample thickness and the distance of the sample from the radiation source had a significant effect during the process, and these two factors should be taken into account during the drying of garlic with an infrared dryer. The maximum drying time (0.53 minutes) was related to the sample with a thickness of 9 mm, which was located at a distance of 10 cm from the surface of the lamp, and the lowest drying time (20.7 minutes) was related to the sample with a thickness of 3 mm, which was in There was a distance of 5 cm from the surface of the lamp.

By reducing the distance of the sample from 10 to 5 cm, due to the increase in the penetration of infrared rays and the increase in the heat transfer rate, the average effective moisture diffusion coefficient from m^2s^{-1} $^{9-}$10 x 71/2 to m^2s^{-1} $^{9-}$10 x 63.3 increased. To model the drying kinetics of garlic, various models were used, and in the end, the Midili model was chosen due to the high coefficient of explanation index and low calculated error, to investigate the kinetics and predict the drying process of garlic slices.

5- Resources

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سایت مجله: **www.fsct.modares.ac.ir**

مقاله علمی_پژوهشی

انتخاب و ارزیابی مدل‌های خشک‌کردن لایه نازک برای توصیف سینتیک خشک شدن برش‌های سیر در خشک‌کن فروسرخ

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اطلاعات مقاله

تاریخ های مقاله :

تاریخ دریافت: ۱۴۰۱/ ۰۴/۱۶

تاریخ پذیرش: ۱۴۰۱/۱۱/۱۳

کلمات کلیدی:

زمان خشک شدن،

سیر،

مدل میدیلی،

نفوذ مؤثر رطوبت.

DOI: 10.22034/FSCT.19.132.377

DOR: 20.1001.1.20088787.1401.19.132.28.1

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چکیده

به‌منظور بهبود بهره‌وری انرژی و افزایش کیفیت محصول خشک‌شده، یک خشک‌کن فروسرخ ساخته شد که می‌توان از آن برای خشک‌کردن میوه‌ها و سبزی‌ها استفاده کرد. در این پژوهش مدل‌سازی سینتیک خشک شدن سیر در یک خشک‌کن فروسرخ بررسی شد. تأثیر فاصله نمونه ها از لامپ پرتودهی در سه سطح ۵، ۷/۵ و ۱۰ سانتی‌متر و اثر ضخامت برش‌های سیر در سه سطح ۳، ۶ و ۹ میلی‌متر بر سرعت انتقال جرم و ضریب نفوذ مؤثر رطوبت در طی فرآیند خشک شدن سیر بررسی شد. برای تعیین مدل سینتیکی مناسب در فرآیند خشک‌کردن، منحنی های خشک‌کردن می‌توانند تحت شرایط تعریف‌شده مورد تجزیه‌وتحلیل قرار گیرند. لذا، در این پژوهش، جهت بررسی سینتیک خشک شدن برش‌های سیر، مدل‌های استاندارد بر داده‌های آزمایشی برازش داده شدند. با افزایش فاصله نمونه‌ها از منبع حرارتی از ۵ به ۱۰ سانتی‌متر، میانگین زمان خشک شدن سیر از ۳۵/۸ دقیقه به ۳۷/۳ دقیقه افزایش یافت. با افزایش ضخامت نمونه‌ها از ۳ به ۹ میلی‌متر نیز میانگین زمان خشک شدن سیر از ۲۲/۷ دقیقه به ۵۰/۹ دقیقه افزایش یافت. اثر فاصله نمونه از لامپ حرارتی فروسرخ و ضخامت نمونه بر تغییرات ضریب نفوذ مؤثر رطوبت سیر بررسی و نشان‌داد که با کاهش فاصله و افزایش ضخامت نمونه‌ها، مقادیر این ضریب افزایش می‌یابد. با کاهش فاصله نمونه از لامپ از ۱۰ به ۵ سانتی‌متر، مشاهده گردید که ضریب نفوذ مؤثر رطوبت از $۲/۷۱\times۱۰^{-۹}\ m^2s^{-1}$ به $۳/۶۳\times۱۰^{-۹}\ m^2s^{-1}$ افزایش یافت. میانگین ضریب نفوذ مؤثر رطوبت برش‌های سیر برای ضخامت‌های ۳، ۶ و ۹ میلی‌متر به ترتیب برابر $۰/۹۴\times۱۰^{-۹}\ m^2s^{-1}$، $۲/۷۲\times۱۰^{-۹}\ m^2s^{-1}$ و $۵/۵۴\times۱۰^{-۹}\ m^2s^{-1}$ بود. در مدل‌سازی فرآیند خشک‌کردن سیر مدل میدیلی نسبت به سایر مدل‌ها با بزرگ‌ترین مقدار ضریب تبیین و کوچک‌ترین خطا، نتایج نزدیک‌تری به داده‌های آزمایش را داشت.