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Dimensionless modeling of thin layer drying process of Aloe vera gel

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Abstract

This research, presents mathematical modeling of drying process of Aloe vera slices with dimensions of 7×4×0.5±0.1 cm. Peeled Aloe vera slices with the initial moisture content of 5750% (d.b) were osmosed for 5 hours in NACL solution of 10% and temperature of 40 °C at a constant solution to fruit ratio of 5:1. Osmosed and unosmosed Aloe vera samples were hot air dried at 55, 70 and 85°C with different air flow rates of 0.015, 0.036 and 0.054 m^3/s for 13200s. The moisture content of Aloe vera samples were measured over different intervals of drying time (1200, 2400, 6000, 9600, 13200s) for each experiment. The experimental results were used to obtain two different dimensionless models based on Buckingham's pi-theorem for both drying methods. To this end, three independent π terms were identified and then the relation between dependent π term and each independent π term was sought. Finally, the dimensionless models incorporating the effect of all the independent π terms on the dependent one derived and evaluated. The RMSE, (R^2), MRD and MBE for the modeling of osmotic-convective drying method were calculated as 0.0185, 0.99, 0.05 and 0.034, respectively. Also these statistical parameters for the convective drying method were as: 0.027, 0.98, 0.061 and 0.051, respectively. Therefore the dimensionless models could predict the moisture content of Aloe vera samples during drying, properly.

Keywords: Aloe vera, Osmotic-air drying, dimensionless model.

Introduction

Aloe vera is a traditional medicinal plant which used in food, pharmaceutical and cosmetic industries. Also it has been utilized to prepare health food drinks, beverage and confectionary. Aloe vera gel could be applied to make creams, lotions and soaps (Pisalkar *et al*, 2011). Some of plants such as Aloe vera leaf have high initial moisture content that it may lead to early spoilage. In other words, the main cause of the decay of fruits and vegetables is their high moisture content (Yadav and Singh, 2014). Drying is one of the most important methods to preserve the foods against decay and spoilage. Indeed, drying process reduces the water activity of the products and controls the microorganism growth (Zomorodian and Moradi, 2010). Also the drying mechanism causes to reduce the weight of the final products and therefore helps to transport the dried grains easier. There are different methods for dehydration of the Aloe vera gel. Osmotic drying is a suitable method because it helps to taste the final products, increasing the shelf life and maintain the quality of the dried gel (Pisalkar *et al*, 2011).

Mathematical modeling usually is used to predict the moisture content of the drying products instantaneously. The mathematical models classify into two categories: theoretical and empirical. The theoretical approach concerns either the diffusion equation or simultaneous heat and mass transfer equations. Having a theoretical model is hard because it needs to solve the governing equations using simplification hypothesizes and thus the derived model does not have admissible accuracy. In the empirical model, a direct relationship is established between the average moisture content and drying time (Akgun and Doymaz, 2005; Akpinar *et al*, 2003; Akpinar *et al*, 2003). Dimensional analysis is an empirical approach which introduces a dimensionless model to explain the relations between dependent and independent π terms.

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This method is a beneficial tool for providing guidance in mathematical modeling and specially simulating the complex phenomena such as those involved in fluid sciences (Giuseppe, 2006; Gibbings, 2011). Several dimensionless models have been proposed to simulate the drying process of bio-products (Melendez *et al*, 2002; Zare *et al*, 2012; Moradi and Karpaprvar fard, 2016). Zare *et al* (2012) developed a generalized dimensionless model of paddy drying from a validated partial differential equation (PDE) drying model using the dimensional analysis of Buckingham theorem.

They considered all drying parameters in an equation to predict the grain moisture content during the drying process. They mentioned that the obtained dimensionless model showed good agreement with the solution results of partial differential equation drying model.

In an another study, a dimensionless model was established and evaluated for drying of corn grains in a continuous dryer equipped with inert energy carrier particles. To do the simulation, five independent π terms which were responsible for the drying rate of the grains were identified and a dimensionless model, includes the effect of all independent π terms on the dependent π term, was derived and evaluated (Moradi and Karparvar fard, 2016). In this research, drying kinetics of Aloe vera gel was investigated at different operating conditions. Dimensional analysis technique was employed to make a predictive dimensionless model for the gel moisture content during drying based on experimental data.

Finding the dimensionless equations for the drying process of the food materials helps to perform a better design of the drying system thus this research is emphasizes to introduce the drying dimensionless models. As we know that no work has been reported on dimensionless modeling of Aloe vera gel during drying process, this study was mainly devoted to establish and evaluate new dimensionless models for thin layer drying of Aloe vera gel.

Therefore the main objective of this research is to define and evaluate the dimensionless model for the drying process of the Aloe vera gel based on Buckingham theorem.

Materials and methods

Aloe vera leaves harvested freshly at the early of morning. During the selection of the leaves for the harvesting, some of important factors such as their uniformity on thickness, color and maturity were considered. Each leaf harvested was cleaned at the start and then peeled by means of a knife to obtain a white gel. The gel samples were cut using the knife with the average dimensions of 0.5×4×7 (±0.1) cm. Aloe vera sample with initial moisture content of 5750% (d.b) was placed in a NACL solution of 10% at a constant solution to fruit ratio of 5:1 for 5 hours. During the osmotic dehydration, the sample with the brine was kept in an incubator at 40°C. Then the pretreated sample in the osmotic solution was dried using a cabinet dryer (Fig.1). In this dryer an electrical fan was used to introduce the ambient air through a heating channel to be heated and then blown to the drying chamber. The dry bulb temperature and the relative humidity of the ambient air were about 27 °C (±2 °C) and 30% (±1%), respectively. An electrical thermostat, with 0.1°C accuracy, in the output of heating channel was installed to fix the drying air temperature as desired value. Aloe vera samples were dried at three different levels of the drying air temperature (55, 70 and 85°C) and the drying air flow rate (0.015, 0.036 and 0.054 m^3/s). These values coincide with those applied in the literature for the osmosed and unosmosed Aloe vera samples. (Pisalkar *et al*, 2011). An adjustable plate was installed on the input of the electrical fan to set the air flow rate of the fan as favorite value.

Before the launching the experiments, intended air temperature and the air flow rate were calibrated by using a Testo 625 (Testo Company, Germany) thermometer with accuracy of ±0.5°C and a Testo 425 anemometer with accuracy of ±0.03m/s, respectively.

The experiments were performed at three

replications. All the above experiments replicated for the control samples (the samples without osmotic pretreatment). During the drying process, Aloe vera gel weighed by means of a digital weighing device (A&D) with 0.001g accuracy at different time intervals (1200, 2400, 6000, 9600, 13200s). The results were used to calculate the dry basis moisture content of the samples

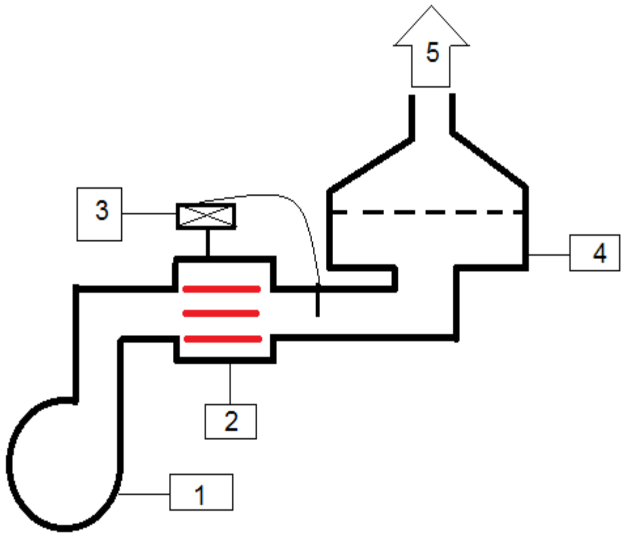

Fig.1.a. Schematic diagram of cabinet dryer

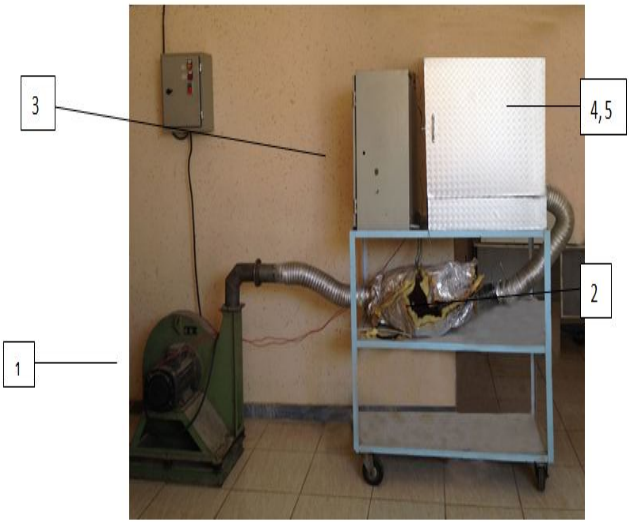

Fig. 1.a. The cabinet dryer used for convective hot-air drying

1-Blower fan 2- Heating canal 3- Air temperature control unit 4- Drying cabinet 5- Outlet of drying air

Osmosis characteristics including solid gain, water loss and weight reduction calculated by the following equations (Yousefi et al, 2013):

$$WR(\%) = \frac{W_0 - W}{W_0} \times 100 \quad (1)$$

$$SG(\%) = \frac{W(1-X_f) - W_0(1-X_0)}{W_0} \times 100 \quad (2)$$

$$WL\ (\%) = SG(\%) + WR\ (\%) \quad (3)$$

Where: WR: Weight reduction, SG: solid gain, WL: water loss, W_0: initial sample weight (g), W: final sample weight (g), X_0: initial moisture content of the sample (decimal), X: final moisture content of the sample (decimal).

Modeling

In order to obtain a dimensionless model, drying parameters must be introduced. The following factors (equation (4)), were recognized to be important in drying process of Aloe vera gel:

$$F\ (M, M_0, K_a, K_0, Q_a, D_{eff}, T_e, T_t) = 0 \quad (4)$$

Where:

M: moisture content of the sample (kg of water per kg of dry matter), M_0: initial moisture content of the sample (kg of water per kg of dry matter), K_a: temperature of drying air (°C), K_0: ambient air temperature (°C), Q_a: flow rate of drying air (m^3/s), D_{eff}: effective moisture diffusivity (m^2/s), T_e: elapsed time (s), T_t: total drying time (s).

Among these, two variables (M and M_0) were merged to produce one π term:

$$MR = M/M_0 \quad (5)$$

The remaining variables (K_a, K_0, Q_a, D_{eff}, T_e, T_t) included three principle dimensions, namely, L (length), T (time), and K (temperature), thus based on Buckingham's pi-theorem (6-3=3), three π terms were constructed as the following:

$$\pi_1 = K_a/K_0,$$
$$\pi_2 = T_e/T_t,$$
$$\pi_3 = (D_{eff} \times (T_t)^{1/3})/Q_a^{2/3} \quad (6)$$

Each of the above π terms were obtained based on their dimensionless process.

Consequently, equation (1) can be rewritten as:

$$MR = f\,[K_a/K_0,\ T_e/T_t,\ [D_{eff} \times (T_t)^{1/3}]/Q_a^{2/3}] \quad (7)$$

Three levels of K_a accompanied by the constant value of K_0=27°C were used to calculate the different values of π_1. Five levels of elapsed time (1200, 2400, 6000, 9600, 13200s) during drying process were selected to measure the moisture content of the samples. To get the π_2 values, the ratios of these time levels to the total time duration of drying (T_t=13200s) were calculated. To obtain the quantities of π_3, at first the effective moisture diffusion coefficients of the drying gel were determined. To attain this goal, analytical solution of drying equation was considered (Khodabakhsh Aghdam et al, 2012):

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

Which; t: drying time (s), L: the half thickness of the slab in the sample (m)

If the variations of the (ln MR) versus (t) take in to account, slope of this variation could be calculated from the equation 6 (Doymaz, 2012):

$$k=\frac{-\pi^2 D_{eff}}{4L^2} \quad (9)$$

In the equation (9), the value of (k) was obtained from the experimental results thus the quantity of the D_{eff} can be easily calculated.

The amounts of diffusion coefficient for osmosed and unosmosed samples were ranged from 3.02×10^{-12} to 4.24×10^{-11} m^2/s and 8.97×10^{-12} to 1.19×10^{-10} m^2/s, respectively.

Three different values of the drying air flow rate (0.015, 0.036, 0.054 m^3/s) were applied at this research. This parameter was measured at the inlet vent of the air (7×7 cm^2) into the drying chamber. To compute the π_3 values, the average quantities of the D_{eff} in the each level of Q_a were used.

These π terms were computed for two different drying methods: the osmotic-convective and convective drying methods. All of the experiments were done at three replications and the average of these values was considered at each treatment.

The values of independent π terms for the osmotic-air dried samples have been presented in Table 1

The following relationship has been proposed to derive the final figuration of dimensionless model (Zare et al, 2012; Eric et al, 2015):

$$MR = A[(F_1(\pi_1))^B.(F_2(\pi_2))^C.(F_3(\pi_3))^D] \quad (10)$$

Where:

$F_1(\pi_1)$, $F_2(\pi_2)$ and $F_3(\pi_3)$ are the best fitted line equations between dependent π term (MR) and each independent π term. A, B, C and D are constants that must be determined.

Also Table 2 shows the values of independent π terms for the air dried samples.

Table1- Different levels of independent dimensionless groups for osmotic-convective samples

$\pi_1=K_a/K_0$	$\pi_2=T_e/T_t$	$\pi_3=(D_{eff}\times(T_t)^{1/3})/Q_a^{2/3}$
2.037	0.091	3.97×10^{-9}
2.593	0.182	4.71×10^{-9}
3.148	0.455	7.18×10^{-9}
	0.727	
	1	

Table2- Different values of independent π terms for air dried samples

$\pi_1=K_a/K_0$	$\pi_2=T_e/T_t$	$\pi_3=(D_{eff}\times(T_t)^{1/3})/Q_a^{2/3}$
2.037	0.091	6.75×10^{-9}
2.593	0.182	8.58×10^{-9}
3.148	0.455	9.87×10^{-9}
	0.727	
	1	

The increase

Results and discussion

Osmosis characteristics (WR, SG and WL), calculated by the equations 1 to 3, were as: 26.5%, 20.3% and 46.8%, respectively. Dimensionless modeling was selected as an empirical procedure to model the drying process of Aloe vera gel at different drying operations. Therefore Eq. 10 was considered as a basic equation to obtain the dimensionless models.

To get the Eq. 10 for each drying state, 80% of experimental data were used to construct the relations between dependent π term and each of the independent π term. The variations of the MR versus different independent π terms have been shown in Figs.2-4. Regression analysis technique was applied on the experimental data to find the best fit between dependent π term and each independent π term. The regression equations and coefficient of determination for both drying methods have been shown in Table3.

The figures 2 to 4 show the variations of MR versus each independent π terms. It can be seen from Fig.2 that MR has been decreased as the π_1 values increased. This may be because the higher air temperature causes to increase the heat transfer rate into the samples. The results are in good agreement with the results of other researchers which have reported increase in drying air temperature cause to decrease the moisture content of the sample (Yousefi et al, 2013; Zomorodian and Moradi, 2010). The best line which characterizes this behavior was also fitted to the experimental data. The relevant line equations have been shown in the Table 3 for two different drying methods (Eqs. 11 and 14).

In the Figure 3, the effects of the π_2 on the M.R of the Aloe vera gel for two drying methods have been illustrated. It was observed the greater drying time ratio (π_2), resulted in the lower MR. The best line, fitted to the experimental data, was also found based on the regression analysis. The line equations and the coefficients of determination have been brought in equations12 and 15. Similar results were obtained by Moradi and Karparvar fard (2016). They reported the variations in MR as the functions of dependent π terms. Also in another research, the variations of MR were shown as the functions of different dependent π terms. (Zare et al, 2012).

Fig.4 shows the changes in MR versus π_3 for two different drying methods. This figure also presents the best line which explains the behavior of the experimental data. The line equations and the coefficients of determination were mentioned in equations 13 and 16 (Moradi and Karparvar fard, 2016; Zare et al, 2012).

Table3- Regression equations and coefficient of determination

Drying state	Regression equations	R^2	Equation no.
	$F_1(\pi_1) = -0.2\pi_1 + 0.8853$	0.99	11
Osmotic-convective drying	$F_2(\pi_2) = 1.1011(\pi_2)^2 - 1.8917\pi_2 + 0.904$	0.99	12
	$F_3(\pi_3) = 3\times10^7\pi_3 + 0.1864$	0.99	13
	$F_1(\pi_1) = -0.1613\pi_1 + 0.7728$	0.99	14
Convective drying	$F_2(\pi_2) = 1.1016(\pi_2)^2 - 2.0388\pi_2 + 0.9624$	0.99	15
	$F_3(\pi_3) = 3\times10^7\pi_3 + 0.0651$	0.85	16

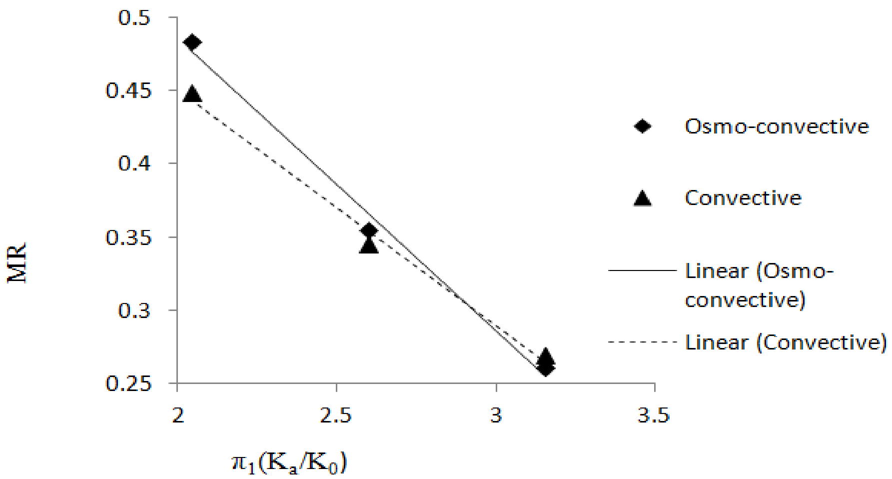

Fig.2. Variations of MR vs. π_1 for two different drying methods

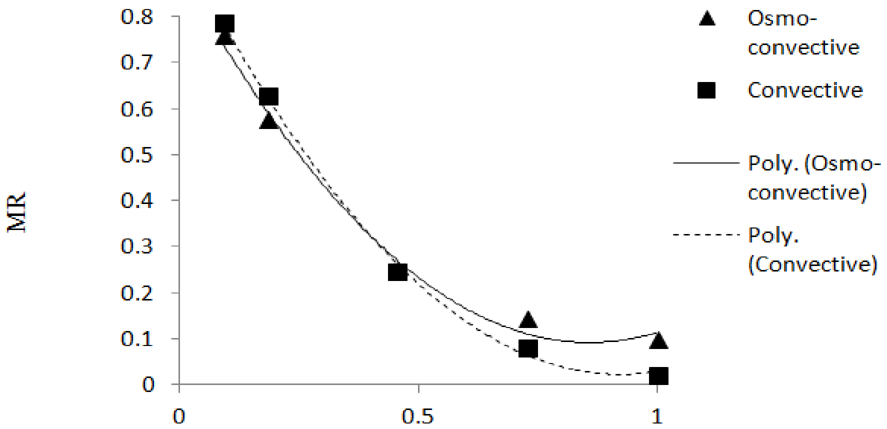

Fig3- Variations of MR versus π_2 for two different drying methods

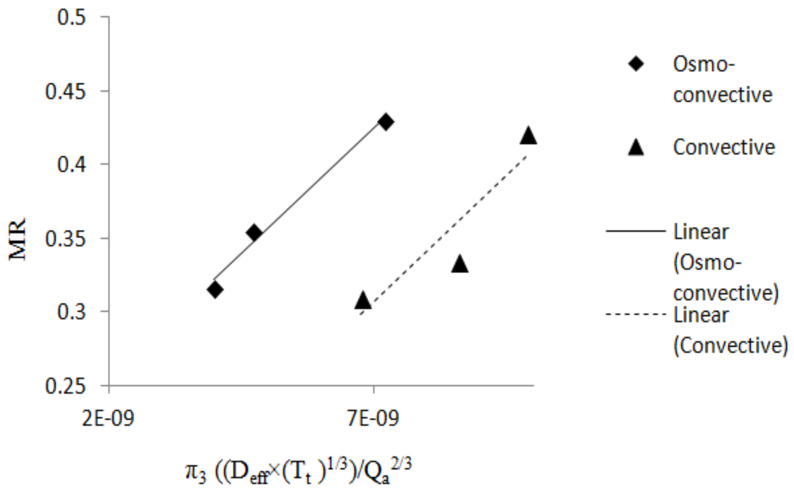

Fig4- Variations of MR versus π_3 for two different drying methods

In order to compute the constants of A, B, C and D in equation 10, an optimizing algorithm was used to reach a minimum value of mean bias error (MBE) (Eric et al, 2015):

$$\beta = \frac{1}{N}\sum_{i=1}^{N}\left|\frac{DR_i^{ex} - DR_i^{pre}}{DR_i^{ex}}\right| \quad (17)$$

Where;

β: MBE, N: number of the experiments, MR_i^{ex}: experimental drying ratio, MR_i^{pre}: predicted moisture ratio.

Hence, the constants for two different drying methods were calculated as follow:

For the osmotic-convective drying method: A= 2.643, B=0.722, C=0.956, D=0.407.

For the convective drying method:

A= 3.514, B=0.594, C=0.956, D=0.568.

Prediction equation

By replacement of the equations 11, 12 and 13 to the equation 10, the dimensionless model for the osmotic-convective drying method was obtained as the equation 18.

$$MR= 2.643\times[-0.2\pi_1+0.8853]^{0.722}\times[1.1011(\pi_2)^2-1.8917\pi_2+0.904]^{0.956}\times[9\times10^7\pi_3+0.0404]^{0.407} \quad (18)$$

Also the dimensionless model for the convective drying method was achieved by setting the equations 14, 15 and 16 in to the equation 10:

$$MR= 3.514\times[-0.1613\pi_1+0.7728]^{0.594}\times[1.1016(\pi_2)^2-2.0388\pi_2+0.962]^{0.956}\times[3\times10^7\pi_3+0.0651]^{0.568} \quad (19)$$

The moisture content of Aloe vera gel can be computed by the equation (20):

$$M=M_0\times MR \quad (20)$$

Evaluating the predicted model

Evaluation of dimensionless models was performed based on comparison between the experimental and predicted moisture ratios. For this purpose, 20% of total experimental data, that did not incorporate in the modeling, were used to validate the derived models. Figs5 and 6 display the experimental MR versus the predicted values of MR for two different drying methods.

+20% and -20% lines show that all predicted data are in the appropriate range (Eric *et al*, 2015).

To validate the goodness of the modeling, three statistical criteria, MBE, RMSE[1], MRD[2] and R^2 were calculated using relations of 17, 21, 22 and 23, respectively:

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}(MR_i^{ex} - MR_i^{pre})^2\right]^{0.5} \quad (21)$$

$$MRD = \left[\frac{1}{N}\sum_{i=1}^{N}\left(\frac{MR_i^{ex} - MR_i^{pre}}{MR_i^{ex}}\right)^2\right]^{0.5} \quad (22)$$

$$R^2 = \frac{\left(\sum_{i=1}^{N}(MR_{exp,i}-\overline{MR}_{exp})(MR_{pre,i}-\overline{MR}_{pre})\right)^2}{\sum_{i=1}^{N}(MR_{exp,i}-\overline{MR}_{exp})^2\sum_{i=1}^{N}(MR_{pre,i}-\overline{MR}_{pre})^2} \quad (23)$$

Where;

N: number of the observations, MR_i^{ex}: experimental moisture ratio, MR_i^{pre}: predicted moisture ratio, $\overline{MR}_{exp}$: the average of experimental moisture ratio, $\overline{MR}_{pre}$: the average of predicted moisture ratio.

The RMSE, R^2, MRD and MBE for the modeling of osmotic-convective drying method were calculated as 0.0185, 0.99, 0.05 and 0.034 respectively. Also these statistical parameters for the convective drying method were as 0.027, 0.98, 0.061 and 0.051. In a similar research, a generalized dimensionless model of paddy drying was developed from a validated partial differential equation and the statistical criteria were reported to be; R^2=0.866, MBE=0.0685 and RMSE=0.014 (Zare et al, 2012). In the another research, a dimensionless model was obtained to predict the moisture content of corn grains into a continuous dryer that R^2, MBE and RMSE were calculated as 0.85, 0.0648 and 0.018, respectively (Moradi and Karparvar fard, 2016). Therefore, the resulted dimensionless models can be used for predicting the moisture content of Aloe vera gel appropriately during thin layer drying process.

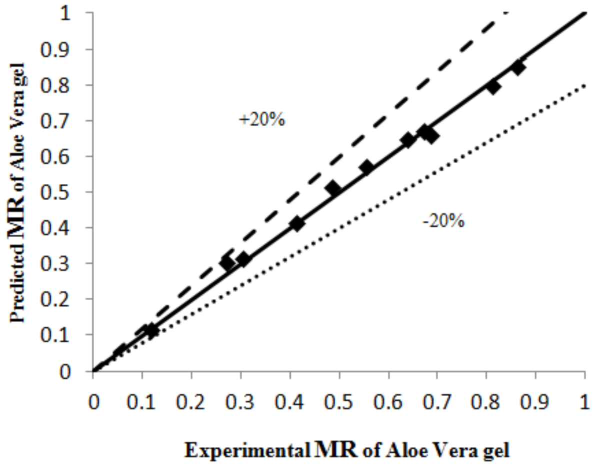

Fig5- Comparison of experimental and predicted MR values for osmotic-convective drying method

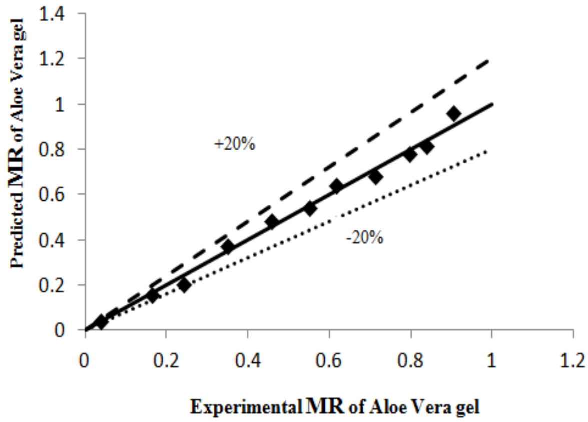

Fig6- Comparison of experimental and predicted MR values for convective drying method

Conclusions

In this research, osmosed and unosmosed Aloe vera samples were dried using a cabinet dryer. Different drying operations were applied on the dryer to obtain the drying kinetics of Aloe vera gels. Finally, two dimensionless equations for predicting the moisture content of Aloe vera gel as it was dried in two different drying methods were derived and evaluated. The statistical results showed good agreement between the

[1] Root Mean Square Error
[2] Mean Relative Deviation

experimental and predicted moisture content. Therefore the resulted equations can easily be used to design the dryer systems of Aloe vera gels.

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چکیده

در تحقیق حاضر مدل سازی فرایند خشک شدن قطعات ژل آلوئه ورا با ابعاد ۰/۱±۰/۵×۴×۷ سانتیمتر ارائه می شود. قطعات پوست گیری شده ژل آلوئه ورا با محتوای رطوبت اولیه ٪۵۷۵۰ (برمبنای خشک) به مدت ۵ ساعت در معرض محلول آب نمک ٪۱۰ تحت دمای ثابت ۴۰°c و با نسبت وزنی ثابت محلول به ژل ۱:۵ قرار داده شدند. نمونه های اسمزی و غیر اسمزی آلوئه‌ورا با هوای خشک کننده تحت دمای ۵۵، ۷۰ و ۸۵ درجه سلسیوس و دبی ۰/۰۱۵، ۰/۰۳۶ و ۰/۰۵۴ متر مکعب بر ثانیه به مدت ۱۳۲۰۰ ثانیه خشک شدند. محتوای رطوبت آلوئه‌ورا در زمان‌های مختلف طی فرایند خشک‌شدن (۱۳۲۰۰، ۹۶۰۰، ۶۰۰۰، ۲۴۰۰، ۱۲۰۰ ثانیه) اندازه‌گیری شد. نتایج آزمایشگاهی جهت بدست آوردن دو مدل بی بعد بر اساس تئوری باکینگهام برای دو روش مختلف خشک‌شدن مورد استفاده قرار گرفت. به این منظور سه گروه بی بعد مستقل شناسایی و سپس رابطه گروه بی‌بعد وابسته با هر کدام از گروه‌های مستقل بدست آورده شد. سرانجام دو مدل بی بعد برای دو روش مختلف خشک شدن با مشارکت اثر همه‌ی گروه‌های بی بعد مستقل بر گروه بی بعد وابسته ایجاد و ارزیابی شدند. میانگین مربعات خطا (RMSE)، ضریب تعیین (R^2)، انحراف نسبی میانگین (MRD) و میانگین خطای انحراف (MBE) برای دو حالت خشک شدن اسمزی- همرفتی و همرفتی به ترتیب عبارتند از: ۰/۰۱۸۵، ۰/۹۹، ۰/۰۵، ۰/۰۳۴ و ۰/۰۲۷، ۰/۹۸، ۰/۰۶۱، ۰/۰۵۱. بنابراین مدل‌های بی بعد به دست آمده می توانند با دقت نسبتاً خوبی محتوای رطوبت ژل آلوئه ورا را حین خشک‌شدن پیش‌بینی کنند.

واژه‌های کلیدی: آلوئه ورا، خشک شدن اسمزی- همرفتی، مدل بی بعد.

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