An Investigation on Drying Kinetics of Chamomile Flower in Vibrofluidized Bed Dryer

Mahmood Reza Rahimi, Roghaye Zamani, and Hossein Sadeghi

***Abstract*—Drying kinetics of chamomile flower at different operating conditions was studied in a vibro fluidized bed dryer "V.F.B.D.," Experiments were carried out in a column with height of 80 cm and ID of 10 cm. Flow rate used range from 29-34m^3h^{-1}, temperature ranged from 40-60℃ and frequency from 7.8-11.8 Hz. Three mathematical models available in the literature were fitted to the experimental data. The accuracies of the models were measured using the correlation coefficient (R^2),root mean square error "R.M.S.E.," and reduced chi-square (X^2). Among the various models tested with experimental data the Henderson and Pabis model was found to be the most suitable for describing drying curves of chamomile flower. The highest value of R^2 and the lowest values of X^2 and "R.M.S.E.," were observed for drying air temperature of 50℃, frequency 11.8 Hz and air velocity 1.2 m/s.**

***Index Terms*—Vibro-fluidized bed dryer, drying kinetics, mathematical modeling, chamomile flower.**

I. Introduction

Increasing popularity of herbal plants has improved their commercial importance. Since they are usually used as dried, determination of their drying characteristics are essential for their preservation and storage in longer periods [1].

Fluidized beds are widely used for the drying of granular solids such as grains, fertilizers, chemicals, pharmaceuticals and minerals [2]. This type of dryers is based on the phenomena of fluidization. Fluidization is the operation by which solid particles are transformed into fluid-like state through suspension in gas or liquid [3].

Fluidized beds as compared to other modes of drying offer advantages such as high heat capacity of the bed, improved rates of heat and mass transfer between the phases and ease in handling and transport of fluidized solids [4]. Chamomile flowers are one of the large and dense particles with poor fluidization quality due to formation of large bubbles in the bed and unable to fluidize in a usual fluidized bed system which leading to partial fluidization or even de-fluidization. For fluidized bed drying, good particle mixing is essential. Thus beds of particles those are difficult to fluidize due to strong polydispersity, particle size, or particle-to-particle adhesive forces, with the ordinary Fluidized bed system, vibration is normally applied to improve the fluidization quality and the mixing effect [5]. There are some reports on the fluidization behaviors for medicinal plant with or without vibration [6], [7].

Fluidized bed technology have been extensively reported for drying various products such as apple [8], green peas [9], olive pomace [10] and castor oil seeds [11]. But information about drying of medicinal plant is very limited. A list of simple semi empirical models commonly used to represent drying kinetics, such as Newton model, Page model, Henderson and Pabis model were detailed, justifying its utility for the design of fluidized beds [4]. Therefore, in this research, the vibro fluidized bed dryer is proposed as an alternative for drying of chamomile flower due to that there are not yet studies available about drying chamomile flower. For these reasons, the aims of present research were:

1) To study the effect of operating conditions on vibro fluidized bed drying kinetics of the chamomile flower at laboratory scale.
2) To fit the drying kinetics with three mathematical models and select the best mathematical model to represent accurately the drying of chamomile flower.

II. Material and Method

A. Plant Material

Chamomile flowers were collected from the region of Norabad (Fars province, Iran) in May 2013. True density of the particles (ρ_p) was determined by liquid pycnometer method using toluene (density equal to 0.87 g/ml at 20℃).

Apparent density (ρ_a) was calculated by weighing the mass of sample by the vessel of known volume. The porosity of the bed was calculated as ($1-\rho_a/\rho_p$).

TABLE I: Characteristics of the Material Coverd in the Present Study

Properties	Value
Mean particle size (d_p), mm	8.54
Particle density (ρ_p), kg m^{-3}	873
Apparent density (ρ_a), kg m^{-3}	337
Voidage (ε_b)	0.61
Shape factor (φ_s)	0.53
Material holdup (kg)	0.20

Shape factor was determined by measuring dimensions of material using a caliper. The properties of the material are summarized in Table I.

B. Drying Equipment and Experimental Procedure

The drying experiments were carried out using a pilot scale

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vibrofluidized bed dryer "V.F.B.D.," designed at the process intensification research laboratory department of Chemical Engineering University of yasouj, Iran. The experimental setup is illustrated in Fig. 1, consists of eight major components: column fluidized bed, oil filter, air flow meter, electrical motor, temperature instrument, a vibration generation system, air heater and central control unit. The cylindrical vibrofluidized bed column is made of acrylic which was 0.80 m high with an internal diameter of 0.1m. This column was separated from a 0.20 m high windbox by a porous plate distributor.

The distributor plate is constructed from stainless steel of 2 mm thickness, which arranged in a triangular pattern. The vibration system consists of an electrical motor where is controlled by means of a belt and springs. Vibration frequency is controlled using an LF inverter with a vibration frequency varying from o to 60 Hz. Drying air was supplied from a high-pressure air source and its pressure was adjusted by a regulator. Air was passed through a rotameter and then was heated by a controlled electrical heater. The temperature of drying chamber controls by a proportional, integral and derivative "P.I.D.," controller with pt-100 type thermocouple within accuracy of ±0.1℃. Two thermocouples located at the bed inlet and outlet measure the temperature of air before entering and after existing of the column.

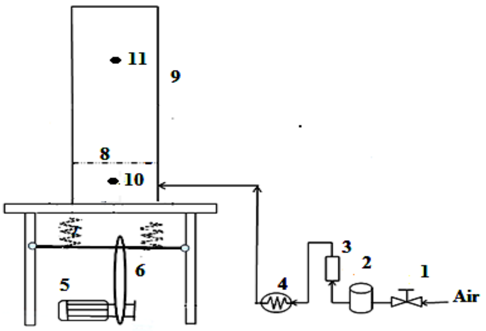

Fig. 1. Schematic diagram of vibrofluidized bed dryer: (1)flow rate regulating valve; (2) oil filter; (3) rotameter; (4) air heater; (5) electrical motor; (6) belt; (7) spring; (8) distributor plate; (9) fluidized bed column; (10, 11) thermocouples.

C. Determination of Moisture Content

The initial moisture contents "M.C.," of fresh chamomile flowers was (83.34±0.7) %. The moisture content was determined using a moisture analyzer (Sartorius MA 35, Germany). Two grams dried sample was put on inside an aluminum pan at temperature of 105℃ for 30 min. The "MC." of dried samples was expressed in percentage on a dry basis.

III. Mathematical Modeling of Drying Curves

For mathematical modeling the equations in Table II were tested to select the best model to describe the drying curve of chamomile flower during drying. The moisture ratio "*MR*" was calculated using the equation $MR=M-M_e/M_0-M_e$ where "*MR*" is the moisture ratio; M is the moisture content at the specific time, M_0 is the initial moisture content and M_0 is the equilibrium moisture content. The moisture contents were expressed on dry basis as kilograms of moisture per kilogram of dry solid. The values of the equilibrium moisture content, M_e are relatively small compared to M and M_0. Thus, the moisture ratio can be calculated as follows [12]: $MR=M/M_0$

The non-linear regression analysis was performed using sigma plot software. The correlation coefficient (R^2) was used to select the best equation to account for the variation in the drying curves of dehydrated sample. In addition to R^2 chi- square (χ^2), the mean square of the deviations between the experimental and estimated values for the models was used to determine the goodness of fit. The lower the values of the chi-square and the higher the values of R^2 values indicate the high fit of the model [13]-[15]. These can be calculated as:

$$\chi^2 = \frac{\sum_{i=1}^{N}(MR_{\exp,i} - MR_{\text{pred},i})}{N-Z} \quad (1)$$

$$R^2 = 1 - \frac{\sum_{i=1}^{N}(MR_{\text{pred},i} - MR_{\exp,i})^2}{\sum_{i=1}^{N}(\overline{MR}_{\text{pred}} - MR_{\text{pred},i})^2} \quad (2)$$

$$\text{RMSE} = [\frac{1}{N}\sum_{i=1}^{N}(MR_{\text{pred},i} - MR_{\exp,i})^2]^{\frac{1}{2}} \quad (3)$$

where $MR_{\exp,i}$ is the ith experimentally observed moisture ratio, $MR_{\text{pred},i}$ the ith predicted moisture ratio, N the number of observation and Z is the number constants.

TABLE II: Mathematical Models Applied to the Drying Curves

Model no	Name of model	Model equation
1	Lewis	MR = exp (-*kt*)
2	Henderson and Pabis	MR = a exp (-*kt*)
3	Page	MR = exp (-kt^n)

IV. Result and Discussion

A. Drying Kinetics

The drying kinetics of chamomile flower dried in a vibrofluidized bed dryer under operating conditions is shown in Fig. 2-Fig. 4. The figures address the effect of operating variables such as the temperature, air velocity and frequency. Fig. 2 show the variations of moisture ratio of the drying samples versus time for different temperature, at *f*=7.8 Hz and *U*=1.03 m/s. The results shown with increasing the temperature of the drying air from *T*=40℃ to *T*=60℃ decreased of moisture ratio. The increase in temperature gets about rise in evaporation rate and effective mass diffusivity which result in higher drying rate. The same results are achieved by plotting moisture ratio versus time in Fig. 3 and Fig. 4. Continuous decrease in moisture ratio indicates that diffusion has governed the internal mass transfer.

Therefore, moisture ratio decreased in specific time with increasing at inlet air temperature, air velocity and frequency.

TABLE III: EVALUATED MODEL PARAMETERS AT VARIOUS OPERATING CONDITIONS

T(°C)	f(Hz)	U(m/s)	Model no	Parameters	χ^2	RMSE	R^2
40	7.8	1.03	1	k: 0.00022	0.0021	0.0431	0.931
50	7.8	1.03	1	k: 0.00030	0.0090	0.0896	0.783
60	7.8	1.03	1	k: 0.00041	0.0046	0.0637	0.916
50	11.8	1.20	1	k: 0.00052	0.0097	0.0870	0.867
50	9.8	1.20	1	k:0.00044	0.0087	0.0878	0.850
40	9.8	1.20	1	k: 0.00027	0.0043	0.0619	0.886
40	9.8	1.03	1	k: 0.00025	0.0004	0.0630	0.867
40	7.8	1.03	2	k: 0.00022, a:0.9342	0.0006	0.0231	0.976
50	7.8	1.03	2	k: 0.00028, a: 0.8417	0.0012	0.0317	0.959
60	7.8	1.03	2	k:0.00040, a: 0.8768	0.0008	0.0248	0.983
50	11.8	1.20	2	k: 0.00053, a: 0.8385	0.0002	0.0122	0.996
50	9.8	1.20	2	k:0.00044, a: 0.8345	0.0008	0.0249	0.983
40	9.8	1.20	2	k:0.00027, a: 0.9065	0.0008	0.0251	0.977
40	9.8	1.03	2	k:0.00022, a: 0.9457	0.0005	0.0196	0.987
40	7.8	1.03	3	k:0.00049, n: 0.9147	0.0005	0.0201	0.985
50	7.8	1.03	3	k:0.00239, n: 0.7585	0.0004	0.0179	0.989
60	7.8	1.03	3	k:0.00147, n: 0.8535	0.0003	0.0139	0.994
50	11.8	1.20	3	k:0.00425, n:0.7486	0.0004	0.0165	0.993
50	9.8	1.20	3	k:0.00288, n: 0.7809	0.0002	0.0126	0.994
40	9.8	1.20	3	k: 0.00094, n: 0.8633	0.0004	0.0178	0.990
40	9.8	1.03	3	k:0.00095, n: 0.8485	0.0005	0.0196	0.987

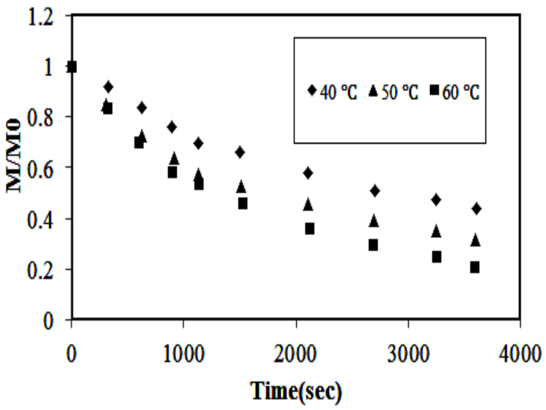

Fig. 2. Drying curves of chamomile flower for different drying air temperatures [*f*: 7.8 Hz, *U*: 1. 03 m/s].

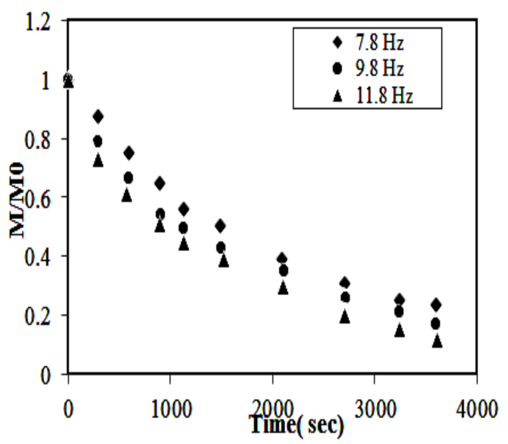

Fig. 3. Drying curves of chamomile flower for different drying frequency [*T*: 50°C, *U*: 1. 2 m/s].

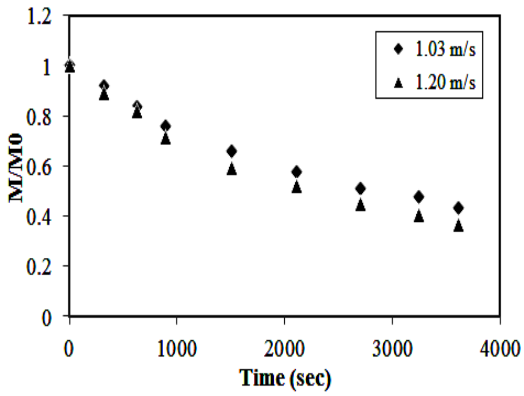

Fig. 4. Drying curves of chamomile flower for different drying air velocity [*T*: 40℃, *f*: 9. 8 Hz].

B. Mathematical Modeling

Experimental results of changes in moisture content were fitted to empirical drying models, namely Lewis model (1), Henderson and Pabis model (2) and Page model (3).

The curve fitting criteria and estimated parameters for drying models for vibrofluidized bed drying of chamomile flower at different operating conditions are summarized in Table III. Fig. 5 compare experimental and predicted moisture ratios with the models versus drying time for chamomile flower dried under different drying conditions. It was found that all the values of R^2 obtained for samples dried in vibrofluidized bed dryer ranged between 0.783 and 0.996 which indicated a good fit. The highest values of R^2 were 0.994 and 0.996 for the page and Henderson–Pabis models, respectively. The lowest values of "RMSE." were found for the Henderson–Pabis model and were in the range from 1.22×10^{-2} to 3.17×10^{-2}. The highest values of R^2 and the lowest values of "R.M.S.E." and χ^2 for the Henderson–Pabis equation indicated, that it gave better predictions than the Page and Lewis models, and satisfactorily described drying characteristics of chamomile flower in vibrofluidized bed dryer.

Falade and Solademi [8], [13] tested four models (Lewis (Newton), Henderson and Pabis, Page, and Modified Page). The high R values (0.9051–0.9983) indicate that the four models fitted very well to the experimental data. The Page and Modified Page models were selected as the suitable models to represent the drying characteristics of sweet potato slices. Doymaz [10], [16] used the Page model and the Henderson and Pabis model to simulate the drying process of olive pomace and found that the Page model gives a very good fit for the moisture content.

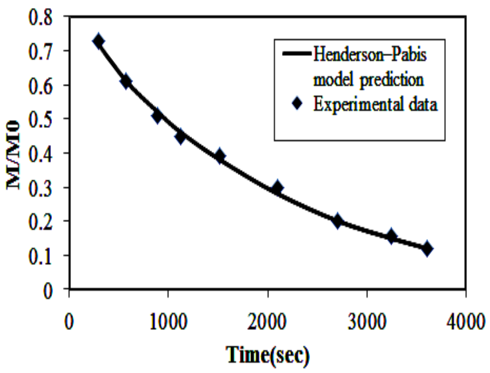

Fig. 5. Comparison of Henderson–Pabis model prediction with the experimental data [*T*: 50℃, *f*: 11.8 Hz, *U*: 1.20 m/s].

APPENDIX

Nomenclature

a, k, n coefficients in models

N number of observations

M moisture content at time t (kg water/kg dry matter)

Z number of constants in a model

M_0 initial moisture content (kg water/kg dry matter)

RMSE root mean square error

M_e equilibrium moisture content (kg water/kg dry matter)

R^2 coefficient of determination

MR moisture ratio (dimensionless)

χ^2 chi-square

$MR_{\exp,i}$ ith experimental moisture ratio (dimensionless)

T drying temperature (℃)

$MR_{\text{pred},i}$ ith predicted moisture ratio (dimensionless)

U velocity (m/s)

f frequency (Hz)

t time, (min)

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