International Food Research Journal 21(4): 1529-1532 (2014)
Journal homepage: http://www.ifrj.upm.edu.my

Generalization of temperature and thickness effects in kinetic studies of turmeric (*Curcuma longa*) slices drying

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Article history

Received: 11 March 2013
Received in revised form: 26 January 2014
Accepted: 28 January 2014

Keywords

Drying kinetic
Superposition Technique
Master curve
Shift factor
Reduced time

Abstract

The effects of temperature and slice thickness on the drying kinetics of turmeric (*Curcuma longa*) slices are modeled to obtain a generalized master curve equation. Drying data obtained from experiments carried out in a laboratory scale tray dryer at different drying temperatures in the range of 40-70°C for different turmeric slice thicknesses (3-10 mm), are fitted to Midilli-Kucuk model ($R^2 > 0.992$), the best fitted model among the common semi-theoretical models. To incorporate the temperature and slice thickness effects, temperature-thickness superposition technique was applied in two stages. In the first stage, at a given drying temperatures moisture ratio is expressed as a function of 'reduced time' ($t.a_h$) which is the product of drying time (t) and a thickness shifting factor (a_h). Thickness reduced master curves obtained at each temperature are again shifted by temperature shift factor (a_T) to generate a single master curve expressing moisture ratio as a function of another reduced time, t″, product of drying time (t), thickness shifting factor (a_h), and temperature shift factor (a_T), to obtain the generalized Midilli-Kucuk model ($MR(t.a_h.a_T)$). Temperature dependence of ah could be regressed into the Arrhenius - type equation, and aT could be regressed into a linear equation. The developed model was compared to the generalized drying model based on generalized drying rate constant, where upon both the models were found to yield prediction of turmeric slice drying with high accuracy (R^2 value > 0.99).

Introduction

Turmeric (*Curcuma longa*), a rhizomatous herbaceous perennial plant of the ginger family, *Zingiberaceae*, is a widely cultivated plant. Its pungent rhizomes produce turmeric, a popular spice for curries, food flavouring, and colouring. The rhizome come as bulb and fingers: bulb is the mother rhizome and fingers are the secondary branches from the bulb. The fingers have approximately circular cross section and have a curved cylindrical shape, 2 to 8 cm long and 1 to 2 cm in diameter, and are easier to grind than the more fibrous bulbs. Turmeric may be commercialized as whole, or ground, or as an oleoresin depending on consumer's preference. The ground form i.e., turmeric powder is quite stable to moderate heat, and when stored in bulk in containers impermeable to moisture and light exposure are is stable up to 6 months (Buescher and Yang, 2000).

Processing of raw bulbs and fingers of turmeric for the production of turmeric powder consists of three stages: curing, drying, polishing and grinding, and these processes assume importance from the view point of the appearance and color of the end product. Turmeric rhizomes needs to be cured before drying. Curing, which essentially involves boiling fresh rhizomes in water, promotes gelatinization of starch, facilitates uniform drying, and increases the dehydration rate. Other benefits include uniform distribution of pigments inside rhizome and a more attractive i.e., unwrinkled dried product that lends itself to easier polishing (Govindarajan, 1980). The rhizomes are sliced before drying to reduce the drying time and improve the quality of the final product as it is easier to achieve a low final moisturelevel in small pieces of rhizome without spoiling the appearance of the product.

Cooked fingers or bulbs are dried until they have a final moisture content of 10-12%. Traditional sun drying can take anything from 10 to 15 days, depending on the climate and the size of the rhizome pieces. Due to the longer duration of drying and non uniformity of heating effect, the occurrence of chemical changes like browning is more prevalent in sun drying method compared to mechanical drying. As a result the sun dried turmeric powder appears darker in colour in comparison to the mechanically dried ones (Bambirra *et al.*, 2008). Present work aims at investing the dependence of moisture removal rate during hot air drying of turmeric slices on drying conditions and slice thickness. The technique of temperature-thickness superposition (Khazaei *et al.*, 2008; Doymaz, 2009) is applied to obtain a generalized model across a range of drying air

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temperatures and slice thicknesses. Such a model, when combined with model of quality degradation during drying, will be quite useful to select drying conditions with predictable quality retention.

Materials and Methods

Raw materials

Turmeric fingers were collected directly from farmers of Napaam village of Tezpur, Assam. Collected turmeric fingers were washed and sorted to obtain fingers of regular shape.

Drying setup

Drying experiments were carried out in a laboratory scale tray dryer (UOP 8 Tray Dryer, Armfield, UK) which can be used to measures the drying kinetic based on the thermo-gravimetric principle. There are carriers for sample trays in the tunnel of the dryer, which is hung from an electronic balance, kept mounted on the top of the dryer. Weight of samples in the trays are continuously measured and displayed by the balance.

Drying experimentation

Drying experiments were carried out at drying temperature of 40, 55 and 70°C; and slice thickness of 3.0, 6.5 or 10.0 mm with 3^2 factorial design. For experimentation, sorted turmeric fingers were cured for about 25-30 min by dipping in boiling water. Following curing, slices were cut into desired thickness; slices were placed in stainless steel trays and dried at set temperature with fixed air velocity in the tray dryer. The turmeric samples were dried until the calculated final weight corresponding to approximately 10% (w.b.) moisture was reached. Each run was performed in an identical manner at an air velocity of 0.85 m/s.

Semi-theoretical drying models

Mass data recorded by an electronic balance was converted to moisture loss data based on measured initial moisture content (M_o) in order to produce the drying curves. M_o was measured on samples collected from drying trays prior to putting in the drying chamber. Moisture ratio (MR) was calculated based on dynamically determined equilibrium moisture content (M_e) values. Then, experimental data of drying curve, MR(t) was fitted to three semi theoretical drying models viz., exponential model, Page model and Midilli-Kucuk model (Eq. 1-3) selected from models used by earlier workers (Midilli *et al.*, 2002; Akpinar, 2006; Sacillik and Elicin, 2006; Wang *et al.*, 2007).

$$MR = \exp(-kt) \quad (1)$$

$$MR = \exp(-kt^n) \quad (2)$$

$$MR = a\exp(-kt^n) + bt \quad (3)$$

Here, k is drying rate constant (min^{-1}), n is an empirical coefficient, t is drying time (min) and a, b are constants. MATLAB curve fitting toolbox was used for determining the model constants: a, b, k and n, and the best fitted model (BM) for drying of turmeric slices was selected based on minimum value of sum square errors (SSE) and R^2 values.

Generalized drying model

The model fitted best (BM) to individual sets of drying data needs to be extended over a range of operating conditions and slice thicknesses for generalization. Two approaches as detailed below were considered.

Generalization of drying rate constant

Effect of slice thickness: For BM, the dependence of the drying rate constant, k on drying temperature and slice thickness variables was then described in the Arrhenius type model (Eq. 4) derived using multiple regression analysis:

$$k = \alpha_0 h^{\alpha_1} \exp\left(\frac{\alpha_2}{T_{abs}}\right) \quad (4)$$

where T_{abs} is the absolute temperature, h is the slice thickness; α_0, α_1 and α_2 are constants.

Technique of master curve

A master curve for all experimental conditions is produced by superimposition of MR(t) plots, shifted to a central condition. In first instance of shifting, MR(t) of three different slice thickness at a given drying temperature can be shifted horizontally on the log(time) axis to a reference slice thickness to obtain the dimensionless time-thickness shift factors, $a_{h,i}$ (Eq. 5).

$$\log a_{h,i} = \log t_R - \log t_i \quad (5)$$

where t_R = time at reference thickness and t_i = time at other thickness, corresponding to given moisture ratio, i is an corresponding to ith thickness. At reference thickness, log ($a_{h,R}$) = 0, or, ah at reference is 1.0. For t_R = t•a_h, called thickness reduced time, t', the horizontal shifting of the drying curve by the magnitude of averaged a_h forms one master curve MR(t') at each of the drying temperatures.

In second instance of shifting, MR(t') i.e., the developed temperature master curves are shifted to a reference temperature to construct a single master curve with the average temperature shift factor of a_T following a equation similar to Eq. (5). The final master curve represented as MR(t″), where $t'' = t \cdot a_h \cdot a_T$, can be used to estimate moisture ratio of turmeric slices at temperature of 40 - 70°C and thickness of 3-10 mm. The final single master curve i.e., MR(t″) was fitted to BM to obtain the best fitted universal moisture ratio master curve as a function of time, temperature and thickness, MR(t,h,T).

Results and Discussion

Comparison and selection of drying model

Drying data of 09 experiments at a constant air velocity of 0.85 m/s were used to estimate the drying rate constant by fitting to three semi theoretical models at different drying temperature and sample thickness. The values of drying rate constant and other constants are tabulated in Table 1-3. From the tabulated values of the goodness of fit (highest R^2, lowest RMSE and SSE) for the three models, the Midilli-Kucuk model was found to be the best model to represent the drying behaviour of turmeric slices at the experimental range of drying temperature and sample thickness.

Drying model parameters and global drying rate constant

The *k* values for the Exponential model increases with the increase in drying temperature, while in case of Page model the value of k decreases with increase in drying temperature. In Midilli-Kucuk model the value of the constant *k* increases with rise in drying temperature and decrease with the increased sample thickness. The increase in k with the increase in drying temperature and decrease of slice thickness indicates that higher temperature and smaller thickness enhanced the driving force of heat and mass transfer. However, *a*, *b* and *n* values did not show any clear trends. Hence, the drying rate constant, *k* (min^{-1}) is correlated by the Arrhenius-type model as given in Eq. (6).

$$k = 1755 h^{-0.62998} exp\left(-\frac{2615.01}{T_{abs}}\right) \quad (6)$$

By inserting function *k* (Eq. (6)) into the 4-term variables Midilli-Kucuk model, it allows the moisture ratio's expression to be reduced to a 3-term variable model known as the single model which is expressed as a function of drying time, drying temperature, and slice thickness (Eq. (7)), with constants *a* = 1.00002, *n* = 1.2664 and *b* = -1.68922 x 10^{-7} fitted using data obtained from entire experimental data.

Table 1. Drying kinetic model parameters for 3 mm thick turmeric slices for Exponential model, Page model and Midilli Kucuk model at three drying air temperatures.

Model			Drying temperature		
			40°C	**55°C**	**70°C**
Exponential Model	Model Parameter	**k**	0.313	0.4117	0.5078
	Statistic of fit	**R^2**	0.934	0.954	0.937
		RMSE	0.087	0.075	0.087
		SSE	0.182	0.067	0.098
Page Model	Model	**k**	0.1854	0.249	0.3107
	Parameters	**n**	1.419	1.501	1.613
	Statistic of fit	**R^2**	0.998	0.978	0.997
		RMSE	0.017	0.015	0.029
		SSE	0.005	0.003	0.005
Midilli Kucuck Model	Model Parameters	**k**	0.2069	0.3029	0.4292
		n	1.260	1.251	1.261
		a	1.022	1.028	1.044
		b	-0.0091	-0.0091	-0.0091
	Statistic of fit	**R^2**	**0.999**	**0.998**	**0.998**
		RMSE	0.017	0.017	0.027
		SSE	**0.004**	**0.003**	**0.005**

Table 2. Drying kinetic model parameters for 6.5 mm thick turmeric slices for Exponential model, Page model and Midilli Kucuk model at three drying air temperatures.

Model			Drying temperature		
			40°C	**55°C**	**70°C**
Exponential Model	Model Parameter	**k**	0.2192	0.3150	0.4142
	Statistic of fit	**R^2**	0.978	0.953	0.938
		RMSE	0.046	0.075	0.088
		SSE	0.049	0.100	0.109
Page Model	Model	**k**	0.1115	0.2097	0.3122
	Parameters	**n**	1.425	1.313	1.274
	Statistic of fit	**R^2**	0.983	0.979	0.999
		RMSE	0.019	0.046	0.011
		SSE	0.079	0.001	0.005
Midilli Kucuck Model	Model Parameters	**k**	1.01	1.039	1.03
		n	-0.0091	-0.009	-0.0091
		a	0.127	0.186	0.2637
		b	1.251	1.252	1.250
	Statistic of fit	**R^2**	**0.992**	**0.994**	**0.999**
		RMSE	0.020	0.027	0.018
		SSE	**0.006**	**0.001**	**0.004**

Table 3. Drying kinetic model parameters for 10 mm thick turmeric slices for Exponential model, Page model and Midilli Kucuk model at three drying air temperatures.

Model			Drying temperature		
			40°C	**55°C**	**70°C**
Exponential Model	Model Parameter	**k**	0.1742	0.2488	0.2684
	Statistic of fit	**R^2**	0.944	0.960	0.945
		RMSE	0.079	0.071	0.081
		SSE	0.088	0.050	0.123
Page Model	Model	**k**	0.0862	0.1171	0.1118
	Parameters	**n**	1.408	1.514	1.618
	Statistic of fit	**R^2**	0.977	0.978	0.988
		RMSE	0.020	0.018	0.012
		SSE	0.005	0.003	0.003
Midilli Kucuck Model	Model Parameters	**k**	1.01	1.026	1.045
		n	-0.009	-0.009	-0.009
		a	0.0968	0.1419	0.201
		b	1.251	1.254	1.260
	Statistic of fit	**R^2**	**0.993**	**0.996**	**0.993**
		RMSE	0.021	0.011	0.011
		SSE	**0.002**	**0.005**	**0.002**

$$MR(t, T, h) = 1.00002 exp(-kt^{1.2664}) + (-1.68922 \times 10^{-7})t \quad (7)$$

(R^2 = 0.998)

Master curve

With the reference of middle value of slice thickness i.e., 6.5 mm the master curve for each temperature was obtained corresponding to thickness reduced time of $t' = t.a_h$. Values of the thickness shift factor ah at three temperatures are shown in Table 4. For determining the temperature dependence of ah Arrhenius-type equation was fitted with R^2 = 0.985 (Eq.8).

$$a_h = 2.816\, h^{-0.4174} exp\left(-\frac{88.99}{T_{abs}}\right) \quad (8)$$

(R^2 = 0.985)

Table 4. Average thickness and temperature shift factors, (a_h and a_t) for turmeric slices 3, 6.5, and 10 mm dried at temperatures of 40, 55 and 70°C

	a_h			a_T
	Sample thickness (mm)			
Temperature (°C)	3.0	6.5	10.0	
40	1.41	1	0.82	0.77
55	1.47	1	0.83	1.00
70	1.41	1	0.8	1.30

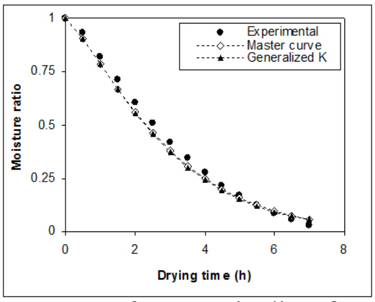

Figure 1. Master curve for turmeric slices fitted to Midilli-Kucuk model obtained after temperature-thickness superposition, and comparison with plot obtained from generalized drying rate constant (k)

Master curves available in terms of $t'=t.a_h$ were shifted again to drying temperature of 55°C, acting as the reference to generate a single master curve (Figure 1) of moisture ratio as a function of reduced time $t''=t.a_h.a_T$. Table 4 lists the values of temperature shift factor a_T corresponding to the three temperatures. The relationship between a_T and temperature, T(°C) was found as given in Eq. 9.

$$a_T = (0.01759T + 0.06933) \quad (9)$$

$R^2 = 0.997$

The final master curve was fitted with the Midilli-Kucuk models ($R^2 = 0.9998$) in order to derive a relationship between moisture ratio, drying time, drying temperature, and slice thickness (Eq. 10).

$$MR(t'',T,h) = 1.00\exp\left[-0.171(t'')^n - 3.63\times10^{-7}(t'')\right] \quad (10)$$

$$t'' = t.(0.01759T + 0.06933)\left(2.816h^{-0.4174}\exp\left(\frac{88.99}{T_{abs}}\right)\right)$$

A comparison of R^2 for the master curve fitted with Midilli-Kucuk model for Eq. (10) generated using the superposition technique ($R^2 = 0.9998$) and the global drying rate constant model in Eq. (7) ($R^2 = 0.998$) indicates that curve shifting based on the time temperature-thickness superposition is a convenient technique to predict the moisture ratio. Both the techniques showed high accuracy in predicting the moisture ratio of turmeric slices conveniently.

Conclusions

Analysis of the results as obtained indicates that a faster drying kinetics is established at higher temperature also at lower sample thickness. Among the tested drying models, Midilli-Kucuk model was best fitted with R^2 value >0.99, which could be developed into generalized drying model in two approaches by (i) globalization of drying rate constant and (ii) the technique of master curve obtained by superposition of temperature and slice thickness effects. Both the techniques yielded generalized model of high accuracy (R^2 value >0.99) for predicting the drying behavior of cured turmeric slices conveniently.

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