Generalized single-layer model for drying kinetics of unpeeled-longan

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Abstract: Dried longan fruit has become an important export product of Thailand. Knowledge about drying kinetics is essential to optimize the drying process. In this study, drying kinetics of unpeeled longan fruits was investigated by varying the parameters as follows: air temperature 50～90℃, relative humidity 4%～20%, air velocity 0.2～0.5 m/s, and size of the fruits. The drying curves of longan fruit, dried in a single layer, were strongly affected by the temperature of the drying air and fruit size but less dependent on relative humidity and velocity of the drying air. Eight single-layer drying models were selected from literature to identify suitable ones for fitting moisture ratio curves to data obtained from the drying experiments. Both, the proportional and exponential coefficient of drying time in the 'Page' model could be given in a generalized function for each of the investigated drying parameters. Moreover, the two coefficients could be correlated to all drying parameters simultaneously. This allowed establishing a generalized 'Page' model for estimating drying curves for any value of temperature, fruit size, relative humidity and air velocity within the range of performed experiments. The analysis also revealed an inner correlation between the two 'Page' coefficients, which opens new doors for further research on the application of the 'Page' model for describing drying processes.

Keywords: drying kinetics, longan, thin-layer model, single-layer model, model
DOI: 10.3965/j.issn.1934-6344.2008.02.064-071

Citation: Sarawut Phupaichitkun, Busarakorn Mahayothee, Thomas Waldenmaier, Joachim Müller. Generalized single-layer model for drying kinetics of unpeeled-longan. Int J Agric & Biol Eng. 2008; 1(2): 64－71.

1 Introduction

Longan (*Dimocarpus longan* Lour) is a member of the *Sapindaceous* family, which is similar to litchi and rambutan. Most of longan in Thailand is cultivated in the northern region, especially in Lumphun and Chiang Mai Province[1]. Since 1995, dried longan fruit has become an important export product of Thailand[2]. Common practice of Thai farmers is to dry the unpeeled longan fruits in a fixed bed hot air dryer, where two tons of longan are dried within 48 hours. To prevent over-drying, the bulk is separated in three layers by plastic nets that are shifted from bottom to top according to a certain time schedule[3-5]. However, mould found in dried longan for export to China indicates that drying still needs to be improved.

To date, several studies on drying kinetics of unpeeled longan have been conducted. These studies, however, are mainly focused on the energy consumption of dryers and are restricted only to a limited number of drying parameters[6,7]. As diffusivity of water has shown to depend on the moisture content of longan, the analytical solution based on Crank (1975) [8] proposed in those studies is not longer valid. Instead of using analytical models, semi-empirical and empirical models

Received date: 2008-10-18 Accepted date: 2008-11-29
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have been applied in order to model drying kinetics and identify optimal drying parameters for agricultural products[9,10]. This group of models was reviewed by Parry (1985) and Al-Muhtaseb et. al. (2004) and later called 'Single-layer model' or 'Thin-layer model'[11-17] Focusing on simple models such as 'Newton', 'Page' and 'Logarithmic' model, the coefficients of these models were fitted to a set of drying parameters[10, 18]. In this research, single-layers of unpeeled longan fruits of different sizes were dried under various drying air conditions in terms of temperature, relative humidity and velocity. The objective was to identify a simple model for drying kinetics and generalized coefficients for the entire range of drying air parameters. This would allow generalizing the results when applied to problems in drying practice.

2 Materials and methods

2.1 Materials

Longan cultivar 'E-Dor' (or 'Daw') bought from an 'Asia-Shop' in Germany (lot 1-3) and from a local market in Thailand (lot 4) was stored in a refrigerator at 4-6℃ and brought to room temperature before starting the drying experiments. Twenty longan fruit samples were measured for size. The width, length and height of fruit were measured, as the shape of the longan was ellipsoid. From the resulting volume a norm radius R_{norm} was derived that represents the radius of a sphere with the equivalent volume[19,20]. In order to prevent overestimation of moisture content *MC* by evaporating volatile substances other than water, *MC* was determined by employing Karl Fischer method using Hydranal – Composite 5 (Riedel-de Haen, Seelze, Germany) on a KF Titrino 785 apparatus (Metrohm, Herisau, Switzerland). Geometry and *MC* of fruits in each lot are shown in Table 1.

Table 1 Weight, moisture content wet basis (MC_{wb}) and geometry of unpeeled fresh longan fruits in four lots (No. 1-3 'Asia-Shop' Germany, No. 4 local market Thailand)

Lot No	weight /g	MC_{wb} /%	Width /mm	Length /mm	Height /mm	R_{norm} /mm
1	11.4	67.5	29.60	25.54	25.23	13.4
2	11.3	67.9	29.76	26.39	25.60	13.6
3	9.4	69.3	27.89	25.27	24.04	12.9
4	11.5	69.1	29.73	25.65	26.12	13.6

2.2 Drying experiments

The drying experiments were carried out using a laboratory dryer of the Institute of Agricultural Engineering, University of Hohenheim, allowing precise control of temperature, relative humidity and air velocity. The dryer is described in detail by Guarte et al (1996)[21]. In this study, drying kinetics of unpeeled longan fruits was investigated by varying the parameters as follows: air temperature 50-90℃, relative humidity 4%-20%, air velocity 0.2-0.5 m/s, and size of the fruits. The fresh longan fruits were classified by norm radius R_{norm} into four sizes from small (＜11.8 mm, mean =11.3 mm), medium (11.8-12.8 mm, mean=12.4 mm), large (12.8-13.8 mm, mean =13.6 mm) to very large (＞13.8 mm mean = 14.5 mm). In Thailand, the average temperature and relative humidity are approximately 30°C and 80% respectively, which is equivalent to a dew point temperature T_{dew} of 28℃. Therefore, all experiments were designed based on this dew point temperature, except the experiments aimed to investigate the effect of relative humidity (code RHxx). The relative humidity was varied from 4% to 20% at a temperature of 80℃. The drying experiment code and drying conditions are shown in Table 2. The drying process was terminated when the water activity of the aril (fruit flesh) was below 0.65.

Table 2 Variation of experimental parameters temperature *T*, air velocity *v*, relative humidity *RH* and fruit size R_{norm}

Code	Temperature T/℃	Air velocity v/m • s^{-1}	Rel. humidity RH/%	Norm radius R_{norm}/mm
T50	50	0.2	31	13.5
T60	60	0.2	19	13.6
T70	70	0.2	12	13.5
T80	80	0.2	8	13.6
T90	90	0.2	4	13.0
R11.3	80	0.2	8	11.3
R12.4	80	0.2	8	12.4
R13.6	80	0.2	8	13.6
R14.5	80	0.2	8	14.5
V0.20	80	0.2	8	12.4
V0.35	80	0.35	8	12.4
V0.50	80	0.5	8	12.3
RH04	80	0.2	4	12.4
RH08	80	0.2	8	12.7
RH12	80	0.2	12	13.4
RH16	80	0.2	16	12.8
RH20	80	0.2	20	12.8

2.3 Evaluation of single-layer drying models

Drying curves were derived from the dimensionless moisture ratio *MR(t)* vs. drying time as given in Eq. (1).

$$MR(t) = \frac{MC(t) - MC_{eq}}{MC_{ini} - MC_{eq}} \tag{1}$$

Where $MC(t)$ is moisture content at time t, MC_{ini} is initial moisture content and MC_{eq} is equilibrium moisture content for set air conditions.

Eight single-layer drying models were selected from literature to identify suitable ones for fitting *MR*-curves to data obtained from the drying experiments. The models are listed together with the number of required coefficients in Table 3.

Table 3 Single-layer drying models used for fitting experimental data

Model name	Model	No. of coeff.	Reference
Newton	$MR = \exp(-C_1 t)$	1	[22]
Page	$MR = \exp\left(-C_1 t^{C_2}\right)$	2	[23]
Henderson and Pabis	$MR = C_1 \exp(-C_2 t)$	2	[24, 25]
Two term exponential	$MR = C_1 \cdot \exp(-C_2 t) + (1 - C_1) \cdot \exp(-C_1 C_2 t)$	2	[26]
Logarithmic	$MR = C_1 \cdot \exp(-C_2 t) + C_3$	3	[27]
Verma et. al.	$MR = C_1 \cdot \exp(-C_2 t) + (1 - C_1) \cdot \exp(-C_3 C_2 t)$	3	[26]
Two term	$MR = C_1 \cdot \exp(-C_2 t) + C_3 \cdot \exp(-C_4 t)$	4	[26]
Modified Henderson and Pabis	$MR = C_1 \cdot \exp(-C_2 t) + C_3 \cdot \exp(-C_4 t) + C_5 \cdot \exp(-C_6 t)$	6	[24, 25]

A nonlinear algorithm was programmed using MATLAB (MathWork, Inc.) for fitting the *MR* models to experimental data. With this process, the optimized coefficients of each model could be obtained. To verify the fitting accuracy, the coefficient of determination R^2 and root mean square error *RMSE* were calculated:

A. Coefficient of determination R^2

$$R^2 = 1 - \frac{R_{SS}}{T_{SS}} \tag{2}$$

where

$$R_{SS} = \sum_{i=1}^{m} \left(MC_{measure} - MC_{predict}\right)^2$$

$$T_{SS} = \sum_{i=1}^{m} \left(MC_{measure} - \overline{MC}_{measure}\right)^2$$

B. Root mean square error *RMSE*

$$RMSE = \sqrt{\frac{\sum_{i=1}^{m} (MC_{measure} - MC_{predict})^2}{m - n}} \tag{3}$$

Where m is number of measured values; n is number of coefficients

2.4 Developing generalized coefficients

The two most accurately fitting models were chosen from a total of eight to identify correlations between the model coefficients C_n and the experimental parameters $X = T$, *RH*, v and R_{norm}. To develop generalized coefficients for each experimental parameter X, major standard functions were applied to all data sets: a) linear function, b) power function c) exponential function, and d) logarithmic function.

a) $C_n = a \cdot (X) + b$

b) $C_n = a \cdot (X)^b$

c) $C_n = a \cdot \exp(X) + b$

d) $C_n = a \cdot \ln(X) + b$

Where X represents T, *RH*, v and R_{norm}, respectively and a and b are coefficients for fitting the functions.

Generalized coefficients C_n were obtained from the best correlation of the standard functions with experimental data evaluated by R^2 and *RMSE*. Based on the generalized coefficients, generalized single-layer drying models were formulated to estimate drying curves $MC(t)$. The best fitting generalized model again was identified by R^2 and *RMSE.*

3 Results and discussion

3.1 Identification of best fitting single-layer models

The best fitting coefficients of the eight single-layer models using temperature as an experimental parameter shows in Table 4. The R^2 values of all models in each experiment were higher than 0.95. This means that all models would be acceptable for describing drying kinetics of longan, even the simplest model, which is the 'Newton' model. Similar results were found for T, *RH*, v and R_{norm}, which are not shown. As differences in R^2 were small, *RMSE* has proven to be more suitable to identify best fitting models. Therefore, *RMSE* is shown in Figure 1 for the individual experimental parameters T, *RH*, v and R_{norm}. As T and R_{norm} have shown much stronger impact on drying kinetics than *RH* and v in experiments, the fitting accuracy for these two parameters is more decisive in choosing best fitting models.

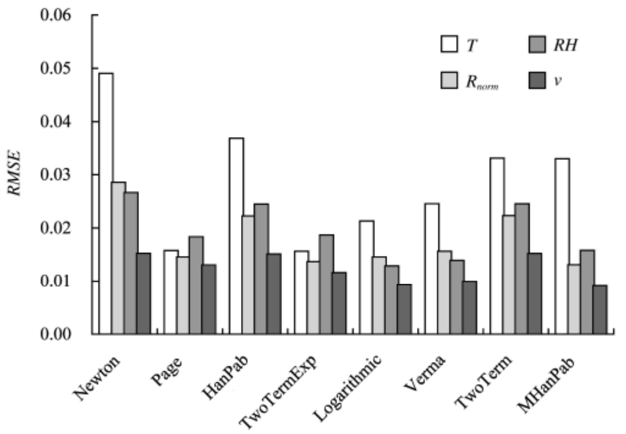


Figure 1 Root mean square error *RMSE* of eight selected single-layer drying models fitted for temperature T, fruit size R_{norm}, relative humidity *RH*, air velocity v and for overall data

Table 4 Coefficients of eight selected single-layer models for fitting experimental data for variation of temperature *T* by maximizing R^2

MODEL	CODE	C_1	C_2	C_3	C_4	C_5	C_6	R^2	*RMSE*
Newton	T50	0.0256						0.9950	0.0400
	T60	0.0437						0.9827	0.0756
	T70	0.0795						0.9984	0.0228
	T80	0.1144						0.9957	0.0327
	T90	0.1369						0.9979	0.0241
Page	T50	0.0164	1.1167					0.9995	0.0131
	T60	0.0199	1.2447					0.9991	0.0173
	T70	0.0690	1.0526					0.9994	0.0142
	T80	0.0913	1.1007					0.9992	0.0145
	T90	0.1282	1.0324					0.9983	0.0217
Modified Page	T50	0.0252	1.1167					0.9995	0.0131
	T60	0.0430	1.2447					0.9991	0.0173
	T70	0.0789	1.0526					0.9994	0.0142
	T80	0.1136	1.1007					0.9992	0.0145
	T90	0.1367	1.0324					0.9983	0.0217
Henderson and Pabis	T50	1.0478	0.0268					0.9977	0.0271
	T60	1.0770	0.0472					0.9902	0.0569
	T70	1.0152	0.0807					0.9987	0.0206
	T80	1.0276	0.1179					0.9969	0.0280
	T90	1.0043	0.1375					0.9979	0.0240
Two Term Exponential	T50	1.6244	0.0326					0.9994	0.0136
	T60	1.7896	0.0616					0.9990	0.0185
	T70	1.4744	0.0932					0.9995	0.0124
	T80	1.5879	0.1438					0.9995	0.0114
	T90	1.0001	0.1369					0.9979	0.0241
Logarithmic	T50	1.0636	0.0249	-0.0288				0.9984	0.0229
	T60	1.1893	0.0344	-0.1566				0.9980	0.0258
	T70	1.0301	0.0753	-0.0264				0.9993	0.0156
	T80	1.0922	0.0969	-0.0899				0.9997	0.0092
	T90	1.0564	0.1181	-0.0706				0.9993	0.0139
Verma	T50	0.0009	0.0255	0.0256				0.9950	0.0400
	T60	-0.3008	0.0045	0.0297				0.9971	0.0312
	T70	-0.6368	0.0475	0.0648				0.9994	0.0141
	T80	-0.4269	0.0397	0.0848				0.9997	0.0080
	T90	-0.0023	-0.1756	0.1320				0.9992	0.0151
Two Term	T50	-0.1689	0.1157	1.1566	0.0290			0.9997	0.0092
	T60	-1.7506	0.0949	2.7334	0.0681			0.9994	0.0147
	T70	-0.2490	0.1785	1.2366	0.0899			0.9996	0.0115
	T80	-1.8057	0.1979	2.7920	0.1593			0.9997	0.0088
	T90	-5.2892	0.0814	6.2733	0.0882			0.9993	0.0143
Modified Henderson and Pabis	T50	1.2510	0.0290	-0.0944	0.0290	-0.1689	0.1157	0.9997	0.0092
	T60	1.3928	0.0543	-0.0012	-0.0619	-0.4012	0.1340	0.9992	0.0161
	T70	-2.5868	0.0577	3.6549	0.0637	-0.0706	0.1352	0.9995	0.0133
	T80	-0.4839	0.1813	1.9610	0.1100	-0.4845	0.0653	0.9999	0.0061
	T90	0.2709	0.1841	0.7421	0.1059	-0.0224	-0.0686	0.9993	0.0134

In terms of *RMSE*, 'Newton' and 'Henderson and Pabis' models-based on one and two coefficients, respectively-showed the lowest quality of fitting. But also the 'Two Term' model with four coefficients and the 'Modified Henderson and Pabis' model with six coefficients showed a low quality of fitting for parameter *T* in spite of the high degree of freedom. Best quality of fitting in terms of the most decisive parameters *T* and R_{norm} was achieved by using the 'Page' and 'Two Term Exponential' models, both based on only two coefficients. Therefore, further analyses were performed on these two models.

3.2 Correlation between coefficients and single experimental parameters

Best fitting standard functions for describing the correlation between the coefficients of 'Page' and 'Two Term Exponential' models and the values of the experimental parameters are presented in Table 5. Instead of temperature *T* in ℃ the absolute temperature T_{abs} in Kelvin was used. Furthermore, the coefficients C_1 and C_2 of the models were examined for inner correlation.

Table 5 Fitting accuracy in terms of R^2 and *RMSE* for the correlation between the coefficients C_1 and C_2 of 'Page' and 'Two Term Exponential' models and the values of the experimental parameters temperature T_{abs}, fruit size R_{norm}, relative humidity *RH* and air velocity *v*

Model	Code	C_1		C_2	
		R^2	*RMSE*	R^2	*RMSE*
Page	C_2	0.7112 (a)			
	T_{abs} /K	0.9565 (a)	0.00889 (a)	0.3542 (a)	0.05970 (a)
	R_{norm} /mm	0.9388 (a)	0.00572 (a)	0.6486 (c)	0.02066 (c)
	RH /%	0.0168 (a)	0.00108 (a)	0.5606 (d)	0.00448 (d)
	v /m • s^{-1}	0.9997 (c)	0.00004 (c)	0.9999 (b)	0.00004 (b)
Two Term Exponential	C_2	0.1932 (c)			
	T_{abs} /K	0.5883 (a)	0.17157 (a)	0.9297 (a)	0.01133 (d)
	R_{norm} /mm	0.6313 (c)	0.05843 (c)	0.9281 (a)	0.00395 (d)
	RH /%	0.4917 (a)	0.01144 (b)	0.6527 (a)	0.00189 (a)
	v /m • s^{-1}	0.9985 (d)	0.00061 (b)	0.7982 (a)	0.00019 (a)

(a) linear function (b) power function (c) exponential function (d) logarithmic function.

For the 'Page' model the coefficient C_1 could be best described in most cases as a linear function of the experimental parameters. However, as the slope is close to being horizontal as in the case of *RH*, small deviations from the line reduced R^2 considerably, whereas *RMSE* was still low. Therefore, the *RMSE* was used as a decisive criterion. The *RMSE* of C_1 was generally lower for the 'Page' model compared to the 'Two Term Exponential' model, for C_2 it was the converse. As an inner correlation between C_1 and C_2 was observable in the 'Page' model, this model was chosen for further analysis. Table 6 shows the functions of the coefficients C_1 and C_2 in dependency of each of the experimental parameters.

Based on the functions for C_1 and C_2 in Table 6, the drying kinetics of longan can be described by the 'Page' model for any value of the individual experimental parameters within the investigated range.

Table 6 Best fitting standard functions for describing the correlation between the coefficients C_1 and C_2 of the 'Page' model and the experimental parameters temperature T_{abs}, fruit size R_{norm}, relative humidity RH and air velocity v

Parameters	C_1	C_2
C_2	C_1= -1.2989 C2+1.1989	
T_{abs} /K	C_1= 0.0029483 T_{abs} -0.14143	C_2= -0.03126 T_{abs} +1.3282
R_{norm} /mm	C_1= -0.018825 R_{norm} +0.35298	C_2= 0.79662exp(0.02228 R_{norm})
RH /%	C_1= -2.5005x10-5 RH +0.11123	C_2= 1.2989 ln(RH)
v /m • s^{-1}	C_1= 0.13281exp(-0.15981 v)	C_2= 1.0362 $v^{0.010648}$

3.3 Correlation between coefficients and combined experimental parameters

The inner correlation of the coefficients C_1 and C_2 of the 'Page' model offered favorable prerequisites for a correlation of the coefficients with combined experimental parameters to establish a generalized model. From the concept of multiple variable analysis, C_1 of the 'Page' model was estimated as being a linear summation of the experimental parameters[28,29]. Similar to the drying constant of the 'Newton' and 'Henderson and Pabis' models, the coefficient 'C_1' in the Page model can be expressed in an elementary form, as being a function of T_{abs} and distance of diffusion represented by R_{norm} of the longan fruit:

$$C_1 = \frac{D_0}{R_{norm}^2} \cdot \exp\left(\frac{E_a}{T_{abs}}\right) \tag{4}$$

Where D_0 is diffusivity and E_a is activated energy.

To make use of this theoretical background, beside standard functions of Table 5, also the correlation of coefficient C_1 to the terms '$1/T_{abs}$' (code Txx) and '$1/R_{norm}^2$' (code Rxx.x) was tested:

$$C_1 = 1884.34 \exp\left(\frac{-3534.40}{T_{abs}}\right) \quad R^2 = 0.8531 \tag{5}$$

$$C_1 = \frac{19.1403}{R_{norm}^2} - 0.007938 \quad R^2 = 0.9037 \tag{6}$$

The good fitting accuracy as shown by high R^2 encouraged to set up a model, based on Eq. (4). Therefore, four models of different complexity for estimating C_1 and C_2 have been established:

Model 1

$$C_1 = \frac{A_1 + A_2 \frac{RH}{v} + A_3 \cdot \exp\left(\frac{A_4}{T_{abs}}\right)}{R_{norm}^2}, \quad C_2=B_1C_1+B_2 \tag{7}$$

Model 2

$$C_1 = \frac{A_1 + A_2 \frac{RH}{v} + A_3 \cdot \exp\left(\frac{A_4}{T_{abs}}\right)}{R_{norm}^2}, \quad C_2=B_2 \tag{8}$$

Model 3

$$C_1 = \frac{A_1 + A_2 \frac{RH}{v} + \frac{A_3}{T_{abs}}}{R_{norm}^2}, \quad C_2=B_1C_1+B_2 \tag{9}$$

Model 4

$$C_1 = \frac{A_1 + A_2 \frac{RH}{v} + \frac{A_3}{T_{abs}}}{R_{norm}^2}, \quad C_2=B_2 \tag{10}$$

Model 1 is the most complex one: C_1 is fitted by four coefficients A_n and C_2 is given as a linear function of C_1 by two further coefficients B_n. To reduce the number of coefficients in model 2, C_2 is a constant. In model 3 the complexity is reduced by replacing the exponential expression of T_{abs} by a linear relation and C_2 is given as a linear function of C_1. The simplest model is model 4, where C_2 is a constant.

Drying curves were estimated with the four models by fitting the coefficients A_n and B_n. Fitting accuracy was measured by R^2 and $RMSE$ and the results are shown in Table 7.

Table 7 Coefficients of different models for estimating C_1 and C_2 of a generalized 'Page' model and fitting accuracy in terms of R^2 and $RMSE$

Model	A_1	A_2	A_3	A_4	B_1	B_2	R^2	$RMSE$
1	-68.448	0.0432	1642.1	-1037.4	-1.2227	1.1974	0.9952	0.03860
2	-179.907	0.0569	718.2	-455.2		1.0829	0.9933	0.04564
3	271.094	0.0675	-89533.5		-1.2453	1.1968	0.9931	0.04626
4	263.818	0.0624	-86918.1			1.0819	0.9923	0.04903

All four models showed a sufficient fitting accuracy documented by high R^2 and low *RMSE* values. Model 1, being the most complex model with the highest number of coefficients, showed the best fitting accuracy. Reducing the number of coefficients also reduced the fitting accuracy. As a compromise between complexity and fitting accuracy, Model 2 with four coefficients and C_2 as a constant were chosen for establishing a generalized 'Page' model for the experimental parameters T, R_{norm}, RH and v:

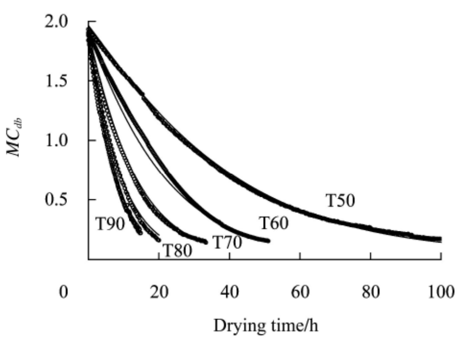
$$MR = \exp\left(\left(\frac{-179907 + 0.05699\left(\frac{RH}{v}\right) + 7182\exp\left(\frac{-4552}{T+27315}\right)}{R_{norm}^2}\right)t^{1.0829}\right) \tag{11}$$

Based on the generalized 'Page' model in Eq. (9), the drying kinetics of longan can now be described for all experimental parameters simultaneously for any value within the investigated range.

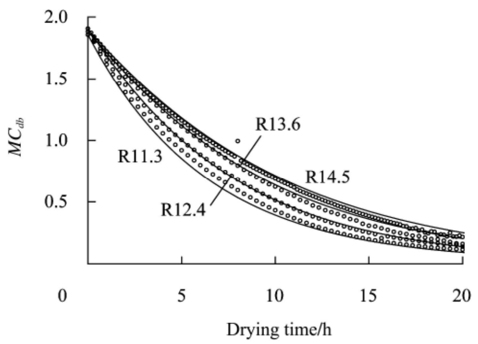
3.4 Description of drying kinetics by a generalized 'Page' model

The experimental data from the drying of longan fruit and drying curves estimated using the generalized 'Page' model as given in Eq. (9) are presented in Figures 2a-d as data points and lines, respectively. The high congruence between the estimated lines and the experimental data points are further proof of the high fitting accuracy of the generalized 'Page' model.

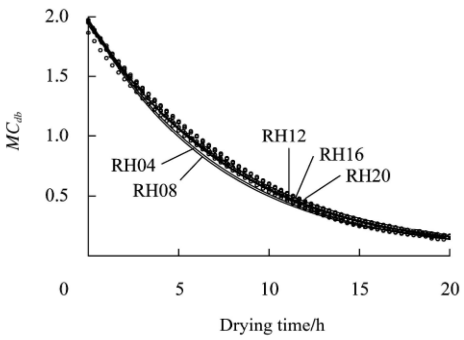
The drying curves of longan fruit, dried in a single layer, were strongly affected by the temperature of the drying air and fruit size but less dependent on relative humidity and velocity of the drying air. Similar to other agricultural products, an increase in temperature and decrease of the fruit size reduces the drying time. As the diffusion coefficient increases with temperature, the water transport via diffusion along the radial direction of the fruit is enhanced by higher temperatures (Fig.2a). Fruit size also affects the drying rate: the larger fruits required a longer drying time than the smaller ones, because of the larger radial distance of diffusion between centre and surface (Fig.2b). Water is removed from the longan surface by convection. Mass flux of water at the fruit surface depends on the concentration of water in the drying air, represented by the relative humidity, and by the mass flow of drying air, represented by air velocity. Therefore, as the humidity decreases and the velocity increases, it is expected that there will be an increase in water removal rate from the fruit surface. Both parameters, however, showed negligible influence on drying kinetics of longan in single-layer drying (Fig.2c,



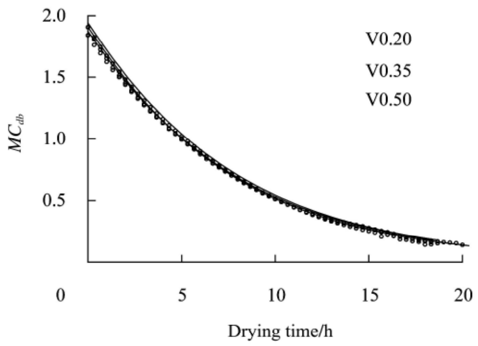
a. Moisture content MC_{db} vs. temperature T
(v=0.2 m/s, T_{dew}=28℃, R_{norm}=13.0-13.6 mm)



b. Moisture content MC_{db} vs. fruit size R_{norm}
(T=80℃, v=0.2 m/s, RH=8%)



c. Moisture content MC_{db} vs. relative humidity RH
(T=80℃, v=0.2 m/s, R_{norm}=12.4-13.4 mm)



d. Moisture content MC_{db} vs. air velocity v
(T=80℃, RH=8%, R_{norm}=12.3-12.4 mm)

Figure 2 Drying curves of longan fruit from experiments (data point) and estimation using the generalized 'Page' model (line)

2d). The same phenomenon of air velocity has been found in the bottom layer during bulk drying of the longan by Klongpanich[30]. This can be explained by the fact that no free water is present on the surface of the longan fruit and therefore the saturation deficit of the drying air is not a limiting factor for drying. Drying kinetics is mainly dominated by the diffusion process inside the fruit, that is, single-layer drying behavior of longan can be called a ‘diffusion controlled process.

4 Conclusions

Kinetics of single-layer drying of longan fruit was mainly determined by the water diffusion process inside the fruit. Therefore, temperature of drying air and fruit size strongly affected the drying process, while less significant effects could be observed from the relative humidity and velocity of the drying air. Amongst various single-layer drying models, the ‘Page’ model performed best to describe the drying behavior of longan fruit. Both, the proportional and exponential coefficients of drying time in the ‘Page’ model could be given in a generalized function for each of the investigated drying parameters. Moreover, by multiple variable analysis based on theoretical background of water diffusion, the two coefficients could be correlated to all drying parameters simultaneously. This allowed establishing a generalized ‘Page’ model for estimating drying curves for any value of temperature, fruit size, relative humidity and air velocity within the range of performed experiments. The analysis also revealed an inner correlation between the two ‘Page’ coefficients, which opens new doors for further research on the application of the ‘Page’ model for describing drying processes.

Nomenclatures

T Temperature (℃)
v Drying air velocity (m/s)
R_{norm} Norm radius of longan fruit (mm)
RH Relative humidity of drying air
$RMSE$ Root mean square error
R^2 Degree of determination
C_n Coefficient of single-layer drying model, n=1,2,3,4,5, and 6
MR Moisture ratio
MC Moisture content (dry basis)
MC_{eq} Equilibrium moisture content
MC_{ini} Initial moisture content (dry basis)
$MC_{measure}$ Measured moisture content
$MC_{predict}$ Predicted moisture content
T_{dew} Dew point temperature (℃)
T_{abs} Absolute temperature (K)
m Number of measurement values
n Number of coefficients
D_0 Diffusivity (m^2/s)
E_a Activation energy of Arrhenius equation
A_n Coefficients for estimating the first coefficients of Page’s model
B_n Coefficients for estimating the second coefficients of Page’s model

Acknowledgments

This work was financially supported by Deutsche Forschungsgemeinschaft (DFG) within the collaborative research program "Sustainable rural development in mountainous regions of Southeast Asia" (SFB 564) of Universität Hohenheim, Germany in cooperation with Silpakorn University, Thailand and Chiang Mai University, Thailand.

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