A Mathematical Modeling Study of Hot Air Drying for Some Agricultural Products

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Abstract

The aim of this paper is to investigate the applicability of simplified mathematical drying models from the research works proposed by several investigators to the drying of some agricultural products. Drying experiments were conducted using a conventional biomass longan dryer at drying air velocity 1.34 m/s and drying air temperature 80°C for red chili peppers, 70°C for lemon grass and 60°C for leech lime leaves. Drying curves obtained from the experimental data were then fitted to the empirical drying models. Thirteen different mathematical drying models were compared according to their coefficients of correlation in order to estimate the drying curves of those products. The results have shown that among the models, the Midilli et al. model was found to be the best model for describing the drying behavior of red chili peppers and leech lime leaves, whereas the Wangh and Singh model was the most suitable for lemon grass.

Keywords: Agricultural Products, Drying, Energy, Food Engineering and Moisture Ratio

1. Introduction

Drying processes play an important role in the preservation of agricultural products. they are defined as a process of moisture removal due to simultaneous heat and mass transfer [1]. The most important reasons for the popularity of dried products are longer shelf-life, product diversity as well as substantial volume reduction. This could be expanded further with improvements in product quality and process applications. The application of dryers in developing countries, especially in Thailand, reduce losses and significantly improve the quality of the dried product when compared to the traditional means of drying such as open sun drying. Not only that, open sun drying is not always suited to large-scale production due to the lack of ability to control the drying conditions properly, the longer drying time, the uncertainties of ambient conditions, large area requirements, insect infestation and the contamination of dust [2]. Consequently, studies based on simulation models are needed for the design and operation of dryers. Hence, the drying characteristics of specific products should be determined. Furthermore, simulation models are also useful in improving the existing drying system. The drying kinetics of materials may be described using the transport properties such as thermal conductivity, thermal diffusivity, moisture diffusivity as well as interface heat and mass transfer coefficients [2].

The investigation of the drying behavior of different agricultural products has recently been carried out by several investigators, for example, green peppers [3], onions [4], red peppers [5-7], rough rice [8], bananas [9], mushrooms [10], potatos [11], grapes [12] and pistachios [13]. All the mentioned agricultural products have the same manner of drying characteristics which are described by the law of exponents. According to the meal habits of Thai people, some of the vegetables are dried during the peak season of harvesting and supplied for consuming during off-season. Red chili peppers, leech lime leaves and lemon grass are the best examples of these kinds of vegetables. They are traditionally consumed in different kinds of meals.

The objective of this work is to study the applicability of several simplified mathematical models selected from the literature to the drying of red chili peppers, lemon grass and leech lime leaves and to fit drying data into the most suitable models by appropriate regression analysis in order to investigate the best model for describing the drying characteristic of some of the agricultural products that are mentioned above.

2. Experimental Setup and a Mathematical Modeling Study

2.1 Experimental Setup

The drying experiments were carried out using a biomass longan dryer which consists of a blower, a combustion chamber, a drying chamber and a ducting system with air recycling as shown in Fig. 1. The drying chamber was constructed from steel sheet as a rectangular dryer of 1.2 m length, 1.2 m width and 1 m height. The Longan dryer is operated by wood fuel combustion for hot air drying. Hot air is fed into the drying chamber for the drying process via the blower. A type K thermocouple was used to measure the temperature at various points of the dryer and connected to a 20-channel data logger (YOKOKAWA model HR 1300 Hybrid Recorder), with reading accuracy of $\pm 0.1^{\circ}$C. The air mass flow rate of air could be calculated from the velocity of air passing through the duct system, which is measured by an air velocity meter (TSI incorporation model 8345 hotwire type). The moisture contents of red chili peppers, lemon grass and leech lime leaves were recorded each hour during the drying process for the determination of drying curves by a digital balance (SARTORIUS MC1 analytic model AC 210s), with reading accuracy of ± 0.00001 g. The same sample of each product was brought out of the drying chamber for weight measurements. From the literature survey, it was found that a suitable drying air temperature for the drying of chilis, lemon grass and leech lime leaves was in the range of 60-80 $^{\circ}$C. In addition, the drying air temperature for drying of chilis, lemon grass and leech lime leaves should be 80 $^{\circ}$C, 70 $^{\circ}$C and 60 $^{\circ}$C respectively. Consequently, the drying air was fixed to 80°C for red chili peppers, 70°C for lemon grass and 60°C for leech lime leaves drying. The drying process was continued from the initial moisture content of 250% db for red chili peppers, 310% db for lemon grass and 165% db for leech lime leaves until the final moisture content reached 13% db for red chili peppers and 12% db for lemon grass and leech lime leaves, which are the desired and appropriate final moisture content as seen in the market. During the experiments, the mass flow rate of air was 0.198 kg/s corresponding to a drying air velocity of 1.34 m/s. The ambient temperature and inlet as well as the outlet air temperature of the drying chamber were also recorded. The positions of the temperature and velocity measurements are shown in Fig. 1.

2.2 A Mathematical Modeling Study

Although the effects of drying air temperature, initial and final moisture content, relative humidity as well as velocity of drying air on the drying constants, were investigated by many researchers [14-16], in this study these parameters were not taken into account. The main objective is to study the correlationship between the moisture ratio (MR) and the drying time at specific and optimum drying conditions, which were surveyed from the literature [17-18]. The MR is usually expressed as $(M-M_e)/(M_o-M_e)$ where M is the moisture content (% db), M_o is an initial moisture content (% db) and M_e is an equilibrium moisture content. However, it could be simplified to M/M_o instead of $(M-M_e)/(M_o-M_e)$, because the relative humidity of the inlet drying air could not controlled, whereas the drying air velocity was controlled. Furthermore, the equilibrium moisture content of agricultural products is not high. This effect was clearly presented by the natural sun drying process [2]. The recorded moisture content of red chili peppers, lemon grass and leech lime leaves in the experiments were then used to plot drying curves. Mathematical modeling of the drying behavior of different agricultural products often requires statistical methods of regression and correlation analysis. Linear and non-linear regression models are important tools to find the relationships between different variables. In this study, the relationships of the constants of the model were determined by a regression technique using an exponential function which is the most common mathematical expression for describing drying characteristics. Drying curves were fitted to the experimental data using thirteen different moisture ratio equations as expressed in Table 1 in order to identify the best model. From Table 1, the constant parameters are the following: a, b and c, whereas the drying constants are k, g and h, respectively. These parameters improve the quality of fit.

Several mathematical drying models applied to drying curves as shown in Table 1 were tested to select the best model based on the quality of fit for describing the drying curve of the red chili peppers, lemon grass and leech lime leaves by choosing the maximum correlation coefficient from regression. The regression analysis was performed using computer software, namely, STATISTICA version 5.0. Regression work was done based on the Quasi-Newton method. The correlation coefficient (r) is the major criterion for selecting the best equation to describe the drying curve.

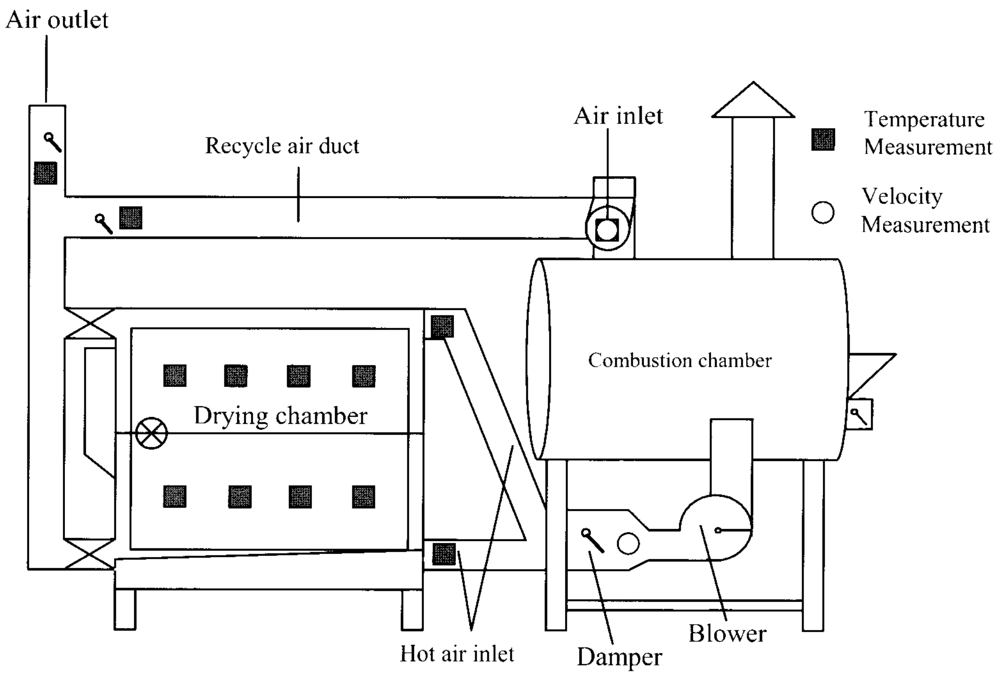

Fig. 1 The configuration of a conventional biomass longan dryer.

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Table 1. Mathematical model of drying curves [1].

Model No.	Model Name	Model Equation
1	Newton	MR = $\exp(-kt)$
2	Page	MR = $\exp(-kt^n)$
3	Modified Page	MR = $\exp[(-kt)^n]$
4	Henderson and Pabis	MR = $a\exp(-kt)$
5	Logaritmic	MR = $a\exp(-kt) + c$
6	Two Term	MR = $a\exp(-kt) + b\exp(-kt)$
7	Two Term Exponential	MR = $a\exp(-kt) + (1 - a)\exp(-kt)$
8	Wang and Singh	MR = $1+at+bt^2$
9	Thompson	$t = a\ln(\mathrm{MR})+b[\ln(\mathrm{MR})]^2$
10	Diffusion Approximation	MR = $a\exp(-kt) + (1 - a)\exp(-kbt)$
11	Verma et al.	MR = $a\exp(-kt) + (1 - a)\exp(-gt)$
12	Modified Henderson and Pabis	MR = $a\exp(-kt) + b\exp(-gt) + c\exp(-ht)$
13	Midilli et al.	MR = $a\exp(-kt^n) + bt$

3. Results and Discussion [19]

The moisture content of red chili peppers, lemon grass and leech lime leaves during the drying process was observed in order to study the behavior of drying. Since the migration of moisture and the evaporation rate from product surfaces to air decreased with decreasing of the product moisture, the drying rate clearly decreased. The drying time is shorter when the temperature is higher, which is explained by the increase in the drying rate. This increase is due to the increased heat transfer potential between the air and the products, thus favoring the evaporation of the water from the products. The effect of temperature on drying rate was well presented in [20].

The change of moisture ratio with drying time of experiments and regression is shown in Fig. 2, Fig. 3 and Fig. 4 respectively. Features of the drying curves are similar to other agricultural products, that is the moisture ratio decreased exponentially. The best model for describing the drying characteristic of red chili peppers, lemon grass and leech lime leaves was selected when the correlation coefficient (r) was the highest value.

The results reveal that the best mathematical model for red chili peppers and leech lime leaves is Midilli et al. when r is 0.99998 where the model is the following:

$$\mathrm{MR} = a\exp(-kt^n) + bt$$

Where $a = 0.999857$

$k = 0.117399$

$n = 1.045196$

$b = -0.003134$

The best mathematical model for lemon grass is Wang and Singh model when r is about 0.99968 where the model is the following:

$$\mathrm{MR} = 1 + at + bt^2$$

Where $a = -0.266254$

$b = 0.018578$

The best mathematical model for leech lime leaves is Midilli et al. when r is about 0.99991 and the constant parameters as well as drying constants are the following: a = 1.00188, $k = 0.284292$, n = 0.839248 and $b = -0.034214$.

The model performance can be evaluated by the percentage of Root-Mean-Square error (RMSE (%)) as expressed in terms of predicted (p_i) and observed (o_i) values given by:

$$RMSE(\%) = \sqrt{\frac{1}{N}\sum_{i=1}^{N}[p_i - o_i]^2} \times 100$$

The difference between the predicted and observed value is a residual. In this paper the RMSE (%) was investigated and shown. RMSE

(%) of the best models for these agricultural products are given in Table 2.

The predicted and observed value for chili peppers, leech lime leaves and lemon grass drying were plotted and shown in Fig. 3, Fig. 5 and Fig. 7, respectively. It was found that the difference between the predicted and observed values are very low. This result is shown by the RMSE (%). This means that the model has very high performance for describing the characteristics of drying curves.

Table 2. RMSE (%) of chilis, lemon grass and leech lime leaves mathematical model.

Agricultural Product	RMSE (%)
Chili	0.00078098
Lemon Grass	0.00444855
Leech Lime Leaf	0.01864375

4. Conclusion

According to the results of the mathematical modeling of the drying of red chili peppers, lemon grass and leech lime leaves, the best model for describing the drying characteristic of red chili peppers and leech lime leaves is Midilli et al., whereas Wang and Singh model is the most suitable for lemon grass. The results of regression analysis indicated that these models could be used to model the drying behavior which is useful for simulation studies of drying systems.

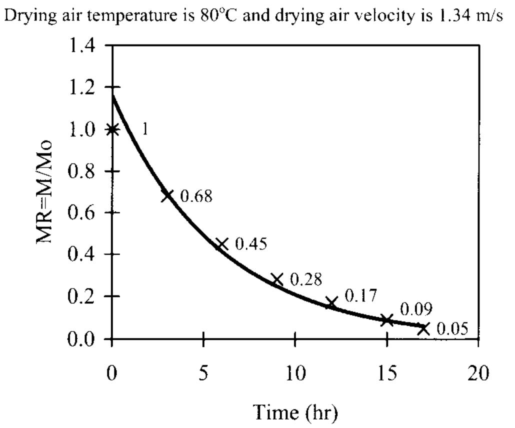

Fig.2 Variation of moisture ratio with drying time for red chili peppers.

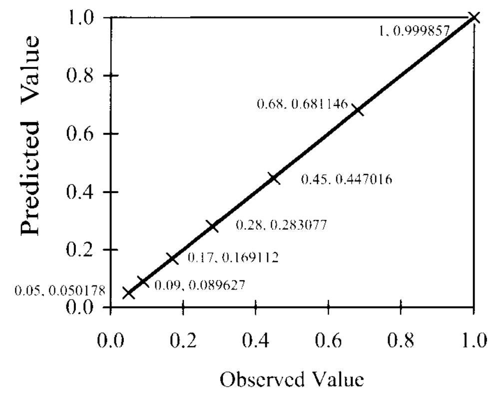

Fig.3 Plot of predicted and observed values for red chili peppers drying modeling.

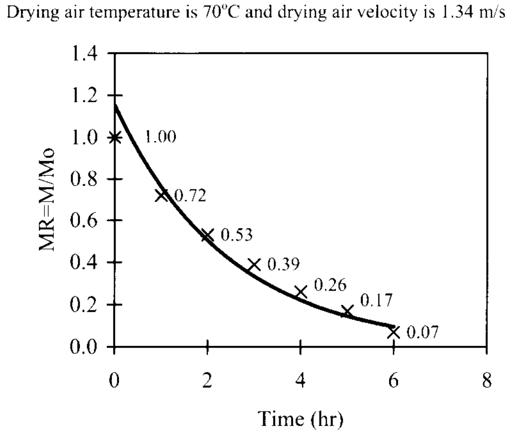

Fig.4 Variation of moisture ratio with drying time for leech lime leafves

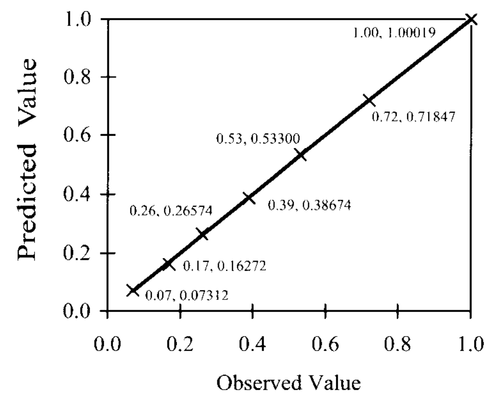

Fig.5 Plot of predicted and observed values for leech lime leaves drying modeling.

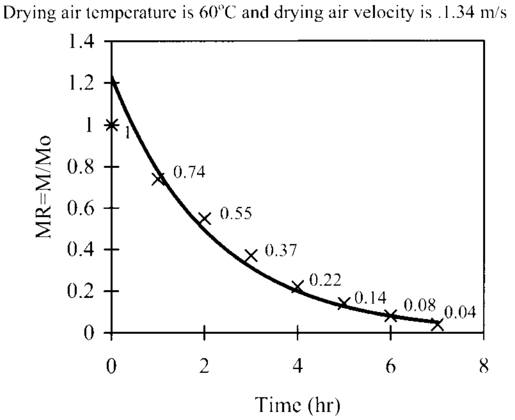

Fig.6 Variation of moisture ratio with drying time for lemon grass.

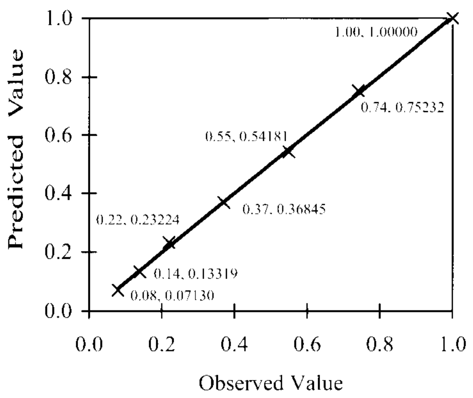

Fig.7 Plot of predicted and observed values for lemon grass drying modeling.

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6. References

[1] Ertekin, C. and Yaldiz, O., Drying of Eggplant and Selection of a Suitable ThinLayer Drying Model, Journal of Food Engineering, Vol.63, pp.349-359, 2004.

[2] Togrul, I. T. and Pehlivan, D., Modelling of Thin Layer Drying Kinetics of Some Fruits under Open-air Sun Drying Process, Journal of Food Engineering, Vol.65, pp. 413-425, 2004.

[3] Yaldiz, O.and Ertekin, C., Thin Layer Solar Drying of Some Vegetables, Drying Technology, Vol.19, pp.583-596, 2001.

[4] Sarsavadia, P. N., Sawhney, R. L. Pangavhane, D. R. and Singh, S. P., Drying Behavior of Brined Onion Slices, Journal of Food Engineering, Vol.40, pp.219-226, 1999.

[5] Passami,V. and Saravia, L.,Relationship Between a Solar Drying Model of Red Pepper and the Kinetics of Pure Water Evaporation I, Drying Technology, Vol.15, No.5, pp.1419-1432, 1997.

[6] E. K. Akpinar, Yasar Bicer, Cingiz Yildiz, Thin Layer Drying of Red Pepper, Journal of Food Engineering, 59, pp.99-104, 2003.

[7] Basunia, M. A. and Abe, T., Thin Layer Solar Drying Characteristics of Rough Rice under Natural Convection,Journal of Food Engineering, Vol.47, pp.295-301, 2001.

[8] Dandamrongrak, R.,Young, G. and Mason, R., Evaluation of Various Pre-Treatments for the Dehydration of Bananaand Selection of Suitable Drying Models, ournal of Food Engineering, Vol.55, pp.139-146, 2002,.

[9] Midilli, A. Olgun, H. and Ayhan, T., Experimental Studies on Mushroom and Pollen Drying. International Journal of Agricultural Engineering Research, Vol. 16, pp.223-244, 1999.

[10] Dimante, L. M. and Munro, P. A., Mathematical Modelling of Hot Air Dryingof Sweet Potato Slices, International Journal of Science and Technology, Vol. 26, pp.99-109, 1991.

[11] Dincer, I., Sun Drying of Sultana Grapes, Drying Technology, Vol.14, pp.1827-1838, 1996.

[12] Midilli, A., Determination of Pistachio Drying Behavior and Conditions in a Solar DryingSystem, International Journal Of Energy Research, Vol.25, pp.715-725, 2001.

[13] Kulkarni,S. D., Bhole, N. G. and Sawarkar, S. K., Dehydration of Soybeans during High Temperature Processing, Drying Technology, Vol.11, No.1, pp.229-240, 1993.

[14] Prabhanjan, D. G., Ramaswamy, H. S. and Raghavan, G. S. V., Microwaveassisted Convective Air Drying of Thin Layer Carrots, Journal of Food Engineering, Vol.25, pp.283-293, 1995.

[15] Temple, S. J. and Van Boxtel, A. J. B.,Thin Layer Drying of Black Tea, Journal of Agriculture Engineering Research, Vol. 74, pp.167-176, 1999.

[16] Jaiut, P., Drying of Bird Chilli using Alternate Hot Air Dryer, Master's Thesis, Postharvest Technology, Chiang Mai University, 76 p, 1999.

[17] Sirisak, S., Lemon – Grass Drying by Producer Gas, Master's Thesis, Energy Technology, King Mongkut's University of Technology Thonburi, 94 p, 2001.

[18] Punlek, C., The Improvement of Longan Dryer Performance for Drying of Agricultural Products, Master's Thesis, Department of Physics, Naresuan University, 121, pp. 2004.

[19] Henderson, Progress in Developing the Thin Layer Drying Equation, Transaction of the ASAE, Vol.17, pp.1167-1172, 1974.