

Thin Layer Drying Model of Sorghum

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Received: August 31st, 2016; Revised: September 26th, 2016; Accepted: November 5th, 2016

Abstract

Purpose: This study was performed to define the drying characteristics of sorghum by developing thin layer drying equations and evaluating various grain drying equations. Thin layer drying equations lay the foundation characteristics to establish the thick layer drying equations, which can be adopted to determine the design conditions for an agricultural dryer. **Methods:** The drying rate of sorghum was measured under three levels of drying temperature (40°C, 50°C, and 60°C) and relative humidity (30%, 40%, and 50%) to analyze the drying process and investigate the drying conditions. The drying experiment was performed until the weight of sorghum became constant. The experimental constants of four thin layer drying models were determined by developing a non-linear regression model along with the drying experiment results. **Result:** The half response time (moisture ratio = 0.5) of drying, which is an index of the drying rate, was increased as the drying temperature was high and relative humidity was low. When the drying temperature was 40°C at a relative humidity (RH) of 50%, the maximum half response time of drying was 2.8 h. Contrastingly, the maximum half response time of drying was 1.2 h when the drying temperature was 60°C at 30% RH. The coefficient of determination for the Lewis model, simplified diffusion model, Page model, and Thompson model was respectively 0.9976, 0.9977, 0.9340, and 0.9783. The Lewis model and the simplified diffusion model satisfied the drying conditions by showing the average coefficient of determination of the experimental constants and predicted values of the model as 0.9976 and Root Mean Square Error (RMSE) of 0.0236. **Conclusion:** The simplified diffusion model was the most suitable for every drying condition of drying temperature and relative humidity, and the model for the thin layer drying is expected to be useful to develop the thick layer drying model.

Keywords: Cross-flow, Circulation, Grain dryer, Sorghum, Simulation

Introduction

Per capita whole grain consumption in Korea rose 12.9% from 2012 to 2013 (Korea Rural Economic Institute, 2016). Whole grain imports increased 1.6 times from 2009 to 2014 due to growing domestic whole grain consumption (Ministry of Agriculture, Food and Rural Affairs, 2015). Sorghum is the fifth-most important cereal crop grown in the world following wheat, corn, rice, and barley, and it has been cultivated as alternative crops because of its great environmental adaptability (Chae and Hong, 2006;

Rural Development Administration, 2012).

Post-harvest processes including drying, storage, processing, packaging, and distribution influence the quality of crop. The drying process is the first stage of post-harvest process. Therefore the drying process is important to maintaining quality because deterioration by inadequate drying process affects the subsequent processes such as storage, processing, packaging, and distribution (Keum et al., 2002). For this reason analyzing the drying process and investigating the drying conditions are important (Keum and Park, 1997). Thin layer drying equations are essential in examining the drying conditions, and they are influenced by the flow rate, temperature and relative humidity of the dry air (Keum and Park, 1997; Keum et al., 2002). The Lewis model, Page

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model, Thompson model, and simplified diffusion model have been widely used for their accuracy and convenience in developing thin layer drying equations of sorghum (Keum and Park, 1997).

The Page model and Thompson model were the most suitable model in the thin layer drying experiment with short grain rice under the conditions of drying temperature of 35~55°C and relative humidity of 30~60% (Keum and Park, 1997). The Page model, Thompson model, simplified diffusion model, and Lewis model were compared in the thin layer drying experiment with green rice under three levels of drying temperature (30, 40 and 50°C) and two levels of relative humidity (30 and 60%), and the Page model was reported to be most adequate to thin a layer drying model for green rice (Han et al., 2006). Most studies about thin layer drying have had a focus on rice, and there has been little research conducted on other cereal crop.

Thus, the purpose of this study was to analyze the drying process so as to examine the drying conditions for sorghum. The drying rate of sorghum was measured under three levels of drying temperature and relative humidity, and the suitability of the Lewis model, Page model, Thompson model, and simplified diffusion model was compared to develop thin-layer drying equations of sorghum.

Materials and Methods

Sample

The sample used in this study was harvested in 2015 at Jeongseon, Kangwon Province, Korea. The sealed sorghum was stored at 2°C cold storage and was left at room temperature 24 hours before the experiment to maintain thermal equilibrium. Initial moisture content was 16.3%, db. that was measured under the conditions of 130°C-10g-18h (ASAE, 2004a).

Thin layer drying apparatus

Air conditioner (MTH4100, SANYO Electric Ltd., Osaka, Japan) that made air in a temperature range between 20 and 70°C ($\pm 0.3^\circ\text{C}$) and relative humidity of 30~98% ($\pm 2.5\%$) was used for this study. The air made by the conditioner was transferred to a plenum chamber and passed through the thin layer sample (Figure 1). Inside temperature of the drying chamber and relative humidity were measured by a hygrometer (TR 72u, T&D Corporation, Nagano, Japan), and air velocity in the chamber was measured at one spot by a hot wire anemometer (VELOCICALC PLUS, TSI, St. Paul, MN, USA), which was decided as 0.56 m/s (± 0.06 m/s) because air velocity should prevent displacement of particles in the thin layer of sorghum (ASAE, 2004b). Weight change of sorghum during drying was measured by an electronic scale (GF-4000, A&D, Tokyo, Japan) in an interval of 10 minutes and saved in the PC. When measuring the weight, the fan operation was stopped to block the air

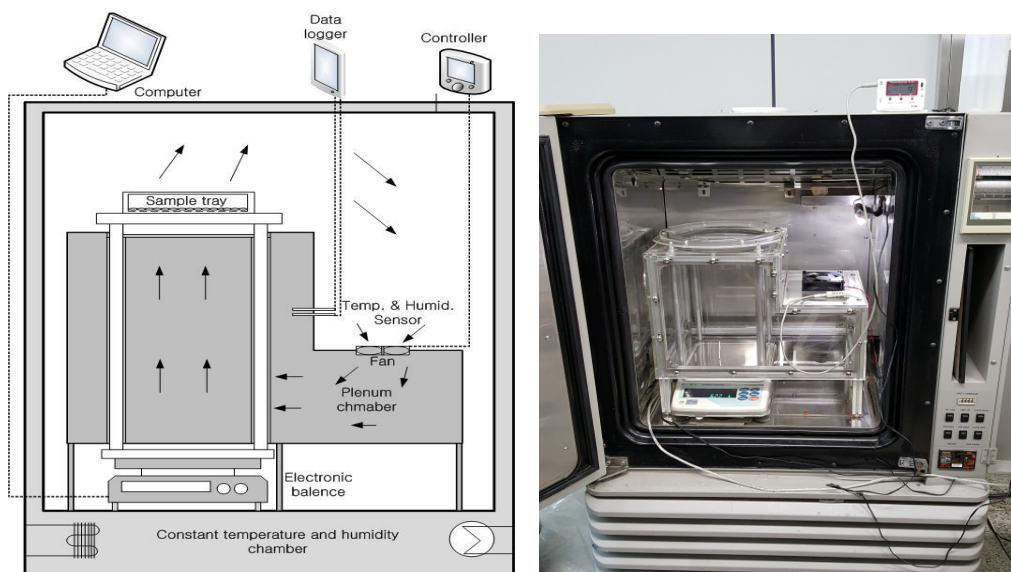


Figure 1. Schematic diagram of the experimental apparatus for drying.

flow in the drying chamber for accurate measurement. Three levels of drying temperature (40, 50 and 60°C) and three levels of relative humidity (30, 40 and 50%) were determined for drying sorghum (ASAE, 2004b). The experiment was repeated three times, and the average value from two experiments was used for the development of drying model while one experiment was used for verification. The sample was dried until the weight change of sorghum became less than 0.1 g, which was considered as equilibrium moisture content.

Thin layer drying models

Eq. (1)~(4) show four adequate models selected among the conventional grain drying equations to determine the thin layer drying equations (Keum and Park, 1997). The Lewis model using Newton's law of cooling, Page model applied to thin layer drying experiment of corn, moisture diffusion model based on the solution of Henderson's Moisture diffusion law, and Thompson model were selected for drying model (Kim et al., 2004).

- Lewis (Lewis, 1921):

$$MR = \exp(-k_1 \cdot t) \quad (1)$$

- Page (Page, 1949):

$$MR = \exp(-P \cdot t^Q) \quad (2)$$

- Moisture diffusion (Henderson, 1952):

$$MR = A \cdot \exp(-k_2 \cdot t) \quad (3)$$

- Thompson (Thompson, 1967):

$$MR = A \cdot \exp(-P \cdot t) + B \cdot \exp(-Q \cdot t) \quad (4)$$

Where, $MR = \frac{M_t - M_e}{M_o - M_e}$

- MR : Moisture ratio (dimensionless)
- M_t : Moisture content (% d.b.)
- M_e : Equilibrium moisture content (dec., d.b.)
- M_o : Initial moisture content (dec., d.b.)
- t : Drying time (hr)
- A, B, k_1, k_2, P, Q : Empirical constants

Parameters were determined by applying empirical constants of moisture ratio to the model using a non-linear regression analysis program of SAS 9.4 (SAS institute, Cary NC), and the parameters of the drying model A, B, k_1, k_2, P, Q were determined as shown in equation (5) by assuming a

function of drying temperature (T_0) and relative humidity (RH_0).

$$A, B, k_1, k_2, P, Q = a_0(T_0) + a_2(RH_0)a_3(T_0)^2 + a_4(T_0 \cdot RH_0) \quad (5)$$

Where,

- a_0, a_1, a_2, a_3, a_4 : Empirical constants
- T_0 : Temperature (°C)
- RH_0 : Relative humidity (dec.)

The combinations of empirical constants were determined using PROC STEPWISE of SAS 9.4 (SAS institute, Cary, NC), and the coefficient of determination and RMSE (Root Mean Square Error) between the empirical constants of moisture ratio and the predicted value by the models were used for verification.

Results and Discussion

Drying rate

Figure 2 shows the changes of moisture ratio based on the drying temperature and relative humidity. The drying rate decreased as a tendency towards the exponential function. When the drying temperature was 40°C, the half response time (Moisture ratio=0.5) of drying that is an index of the drying rate was observed as 2.5 hours at a relative humidity of 30%, 2.5 hours at 40%, and 2.8 hours at 50%. The same half response time was observed at the relative humidity of 30% and 40%, and it increased sharply at 50%.

When the drying temperature was 50°C, the half response time of drying was observed as 1.8 hours at a relative

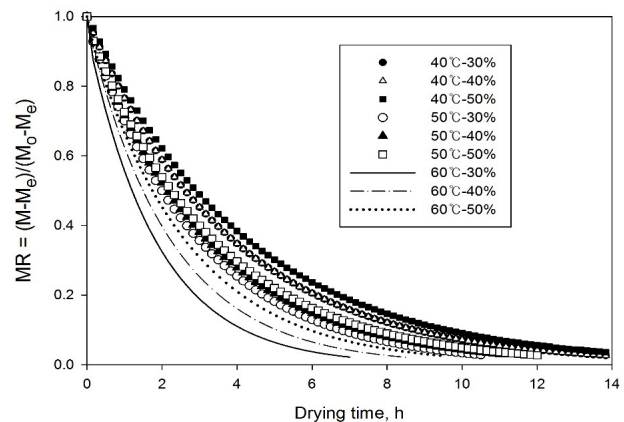


Figure 2. Drying curves of sorghum under various drying temperatures and relative humidity.

humidity of 30%, 2.0 hours at 40%, and 2.2 hours at 50%. The half response time increased with increasing relative humidity.

When the drying temperature was 60°C, the half response time of drying was observed as 1.2 hours at a relative humidity of 30%, 1.3 hours at 40%, and 1.6 hours at 50%. The half response time increased with increasing relative humidity. The half response time increased significantly at a relative humidity of 50%, and there was no significant difference between the relative humidity of 30% and 40%.

The half response time of drying was affected by both drying temperature and relative humidity, and it decreased with increasing drying temperature and decreasing relative humidity.

Thin layer drying model

Table 1 shows the experimental constants and coefficient of determination of the Lewis model, Page model, simplified diffusion model, and Thompson model, and the coefficient of determination was obtained from drying temperature and relative humidity. The coefficient of determination of A in the simplified diffusion model and B in the Thompson model were observed as low due to the difference of starting point on the model as 0.8254 and 0.7881, respectively. However, the coefficients of determination of the other

models were fitted well and were greater than other model's coefficient of determination.

The coefficients of determination and RMSE between the empirical constants of moisture ratio and the predicted values by the models that were used for verification of four drying equations were provided in Table 2. The Lewis model was calculated to be in good agreements with overall drying conditions by showing the coefficient of determination of 0.9976 and RMSE of 0.0236, and the simplified diffusion model was most fitted in all drying conditions with the coefficient of determination of 0.9977 and RMSE of 0.0228. The Page model and Thompson model were less fitted than the Lewis model and simplified diffusion model by showing the coefficient of determination of 0.9340 and RMSE of 0.0992. Therefore, drying characteristics of sorghum was significantly able to predict at various drying conditions (temperature and RH) with the simplified diffusion model.

Figures 3~5 present the comparison between the empirical constants of moisture ratio and the predicted values by the models under the conditions of drying temperature of 40°C and relative humidity of 30, 40, and 50%.

The empirical constants of moisture ratio agreed well with the predicted values when the relative humidity was high in the Lewis model and simplified diffusion model. In

Table 1. Estimated values of experimental coefficients for drying models

Model	Experiment coefficients	R ²
Lewis	$k_1 = 0.28267 - 0.01587(T_0) + 1.20625(RH_0) + 0.3(RH_0)^2 - 0.03682(T_0 \cdot RH_0)$	0.9839
Page	$P = -0.14174 + 0.00442(T_0) + 1.57358(RH_0) + 0.987(RH)^2 - 0.02652(T_0 \cdot RH_0)$	0.9817
	$Q = -0.44713 + 0.01221(T_0) + 5.36783(RH_0) - 4.17(RH_0)^2 - 0.01355(T_0 \cdot RH_0)$	0.9954
Simplified diffusion	$A = 1.16067 - 0.00757(T_0) + 0.15892(RH_0) - 0.24(RH_0)^2 - 0.00127(T_0 \cdot RH_0)$	0.8254
	$k_2 = 0.3112 - 0.017(T_0) + 1.23142(RH_0) + 0.165(RH_0)^2 - 0.0347(T_0 \cdot RH_0)$	0.9864
Thompson	$A = 0.00891 + 0.20888(T_0) - 34.70158(RH_0) + 45.1(RH_0)^2 - 0.05078(T_0 \cdot RH_0)$	0.9925
	$B = -0.23004 + 0.01083(T_0) - 0.19397(RH_0) + 0.11567(RH_0)^2 + 0.00174(T_0 \cdot RH_0)$	0.7881

T_0 : Drying temperature.

RH_0 : Relative humidity.

A, B, k_1 , k_2 , P, O : Empirical constants.

Table 2. Estimated coefficients of determination and root mean square error of moisture ratio for drying models

Model	R ²	RMSE
Lewis	0.9976	0.0236
Page	0.9340	0.0992
Simplified diffusion	0.9977	0.0228
Thompson	0.9783	0.0697

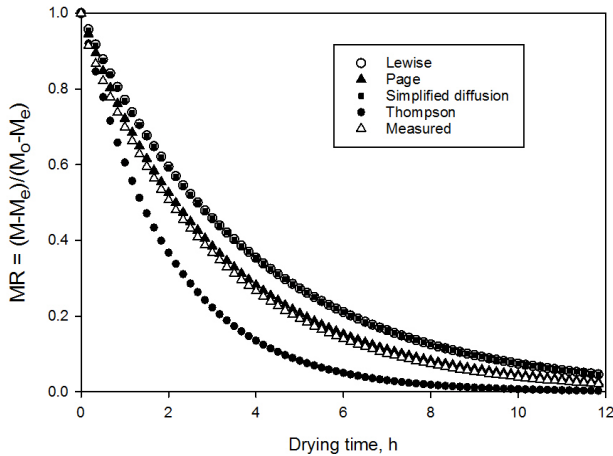


Figure 3. Comparison of the measured and predicted moisture ratio by four different drying models under the conditions of drying temperature of 40°C and relative humidity of 30%.

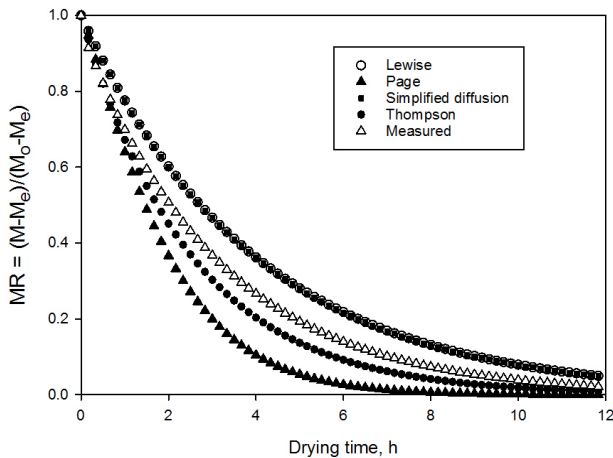


Figure 4. Comparison of the measured and predicted moisture ratio by four different drying models under the conditions of drying temperature of 40°C and relative humidity of 40%.

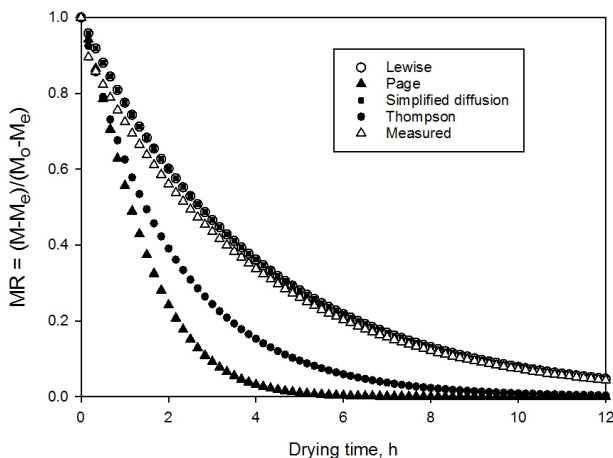


Figure 5. Comparison of the measured and predicted moisture ratio by four different drying models under the conditions of drying temperature of 40°C and relative humidity of 50%.

the Page model, the empirical constants of moisture ratio agreed well with the predicted values when the relative humidity of 30%, but error increased with increasing relative humidity. In the Thompson model, significant errors under all levels of relative humidity were observed.

Figures 6~8 show the comparison between the empirical constants of moisture ratio and the predicted values by the models under the conditions of drying temperature of 50°C and relative humidity of 30, 40, and 50%.

The empirical constants of moisture ratio agreed well with the predicted values under all levels of relative humidity in the Lewis model and simplified diffusion model, and after drying time of 4 hours very good agreement was observed. In the Page model and Thompson model, significant errors under all levels of relative humidity were observed.

Figures 9~11 provide the comparison between the empirical constants of moisture ratio and the predicted values by the models under the conditions of drying temperature of 60°C and relative humidity of 30, 40, and 50%.

The predicted values in the Lewis model and simplified diffusion model showed a slight error at a relative humidity of 50%, and they showed good agreement at a relative humidity of 30% and 40%. In the Page model, the predicted values were fitted well with the empirical constants at a relative humidity of 50%, but they showed a significant error at 30% and 40%. In the Thompson model, the error between empirical values and predicted one decreased with increasing drying time.

Figure 12 shows the comparison between the simplified diffusion model developed in this study and thin layer drying equation suggested by Paulsen and Thompson (1973) under the conditions of three levels of drying temperature (40, 50, and 60°C) and relative humidity of 40%. The difference in moisture ratio increased with increasing drying time in all drying conditions. The predicted values from the Paulsen and Thompson (1973)'s model were calculated with only drying temperatures but the developed model used with temperature and relative humidity. This made the difference in the moisture ratio between two models. Therefore, the simplified diffusion model is more appropriate to predict the drying characteristics for the domestic sorghum comparing with Paulsen and Thompson (1973)'s model.

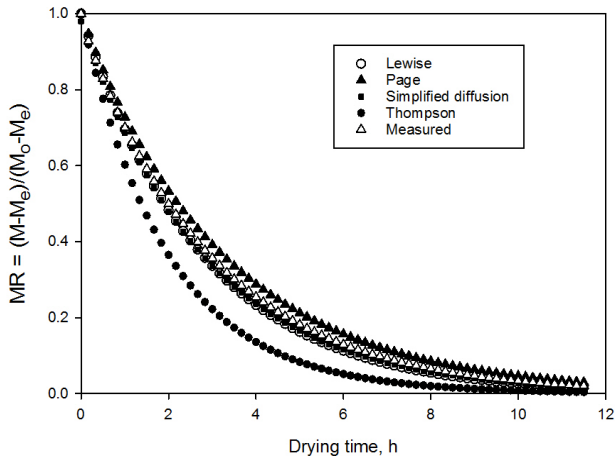


Figure 6. Comparison of the measured and predicted moisture ratio by four different drying models under the conditions of drying temperature of 50°C and relative humidity of 30%.

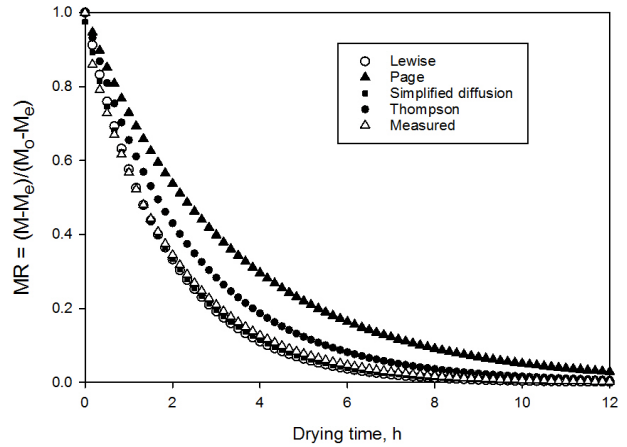


Figure 9. Comparison of the measured and predicted moisture ratio by four different drying models under the conditions of drying temperature of 60°C and relative humidity of 30%.

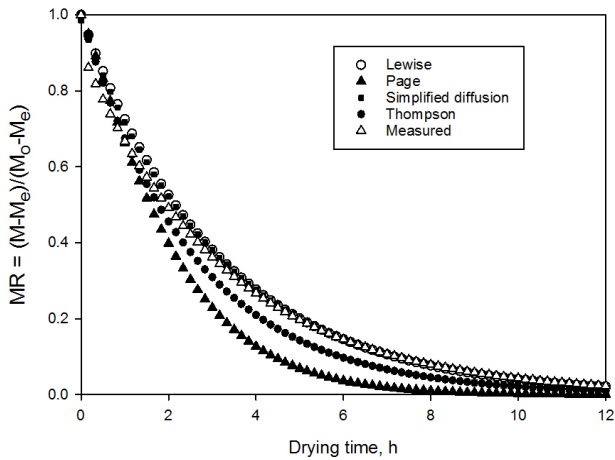


Figure 7. Comparison of the measured and predicted moisture ratio by four different drying models under the conditions of drying temperature of 50°C and relative humidity of 40%.

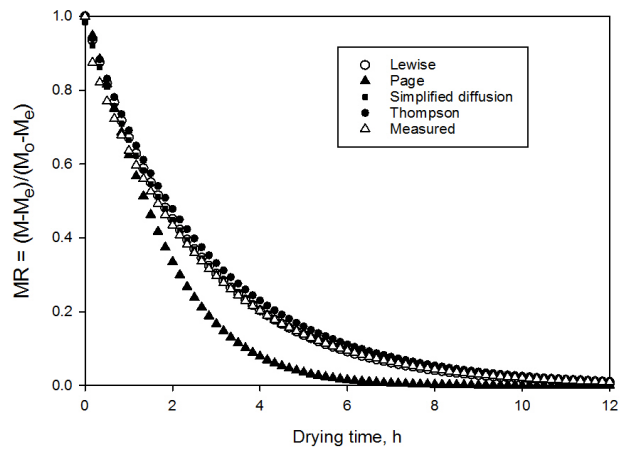


Figure 10. Comparison of the measured and predicted moisture ratio by four different drying models under the conditions of drying temperature of 60°C and relative humidity of 40%.

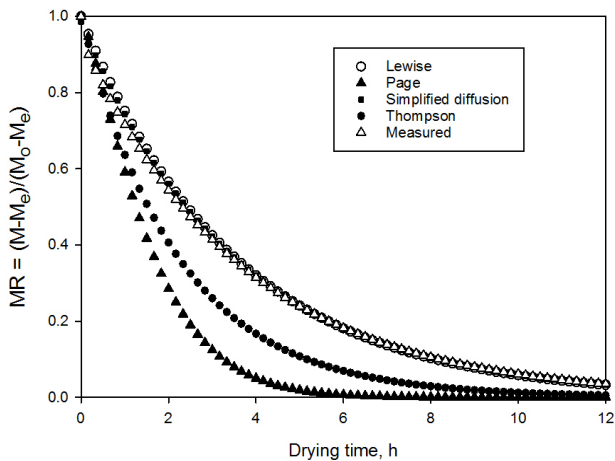


Figure 8. Comparison of the measured and predicted moisture ratio by four different drying models under the conditions of drying temperature of 50°C and relative humidity of 50%.

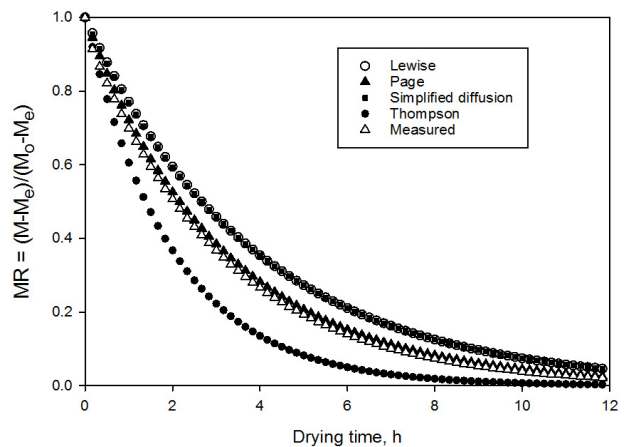


Figure 11. Comparison of the measured and predicted moisture ratio by four different drying models under the conditions of drying temperature of 60°C and relative humidity of 50%.

Conclusions

The drying rate of sorghum was measured under the conditions of three levels of drying temperature (40°C, 50°C and 60°C) and relative humidity (30%, 40% and 50%). The constants in the experiments were determined, and their suitability was compared by examining the Lewis model, Page model, simplified diffusion model, and Thompson model. The drying rate decreased as a tendency towards the exponential function. The half response time (Moisture ratio=0.5) of drying that is an index of the drying rate increased with increasing relative humidity under the same drying temperature, and it decreased with increasing drying temperature under the same relative humidity. Thus, the half response time of drying was affected by both drying temperature and relative humidity, however, greater influence was observed from the drying temperature.

The coefficient of determination of A in the simplified diffusion model and B in the Thompson model were observed as low due to the difference of starting point on the model as 0.8254 and 0.7881, respectively. However, the coefficients of determination of other models were fitted well by showing over 0.98.

The Lewis model showed the coefficient of determination of 0.9976 and RMSE of 0.0236, and the simplified diffusion model showed the coefficient of determination of 0.9977 and RMSE of 0.0228. The Page model showed the coefficient of determination of 0.9340 and RMSE of 0.0992, which was less fitted than the Lewis model and simplified diffusion model. The Thompson model showed the coefficient of determination of 0.9783 and RMSE of 0.0697. Thus, the simplified diffusion model was shown to be the most suitable for the thin layer drying model of sorghum at all drying conditions of temperature and relative humidity. Consequentially, the design factors of a dryer for domestic sorghum are supposed to be defined using the results of this study.

Conflict of Interest

The authors have no conflicting financial or other interests.

Acknowledgement

This work was supported by a grant from Korea Institute

of Planning and Evaluation for Technology in Food, Agriculture, Forestry and Fisheries(IPET) in Gyeonggi-Do, Korea (315036-3).

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