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Equilibrium Moisture Content Modeling and Study of Circulating-Bed Drying Kinetics of Non-Fragrant and Fragrant Paddy Varieties

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Abstract

Due to maintaining good quality of rice grain kernel varieties during post-harvesting and in-store period, the thermos-physical properties which relate to surrounding conditions (temperature and relative humidity) of each rice variety are essential, especially on its moisture content and diffusion mechanism. Therefore, the main objectives of this research are to determination of the thermo-physical properties (in terms of equilibrium moisture content (EMC) and effective diffusivity (D_{eff})) of local non-glutinous GorKhor55 (RD55) and Hom Thammasat (HT) paddy varieties and to field experiment study of the small-scale circulating-bed dryer with capacity of 1 - 1.5 ton. The EMC experiment using gravitational method is carried on and the experimental results are simulated by non-linear regression analysis. The results show that the predicted data using Modified Oswin model is the most suitable fitting to the exact EMC data for both paddy varieties. The effective diffusivity of both paddy varieties is the function of inlet drying temperature. For the last purpose of this work, the drying kinetics of RD55 and HT paddy varieties with initial moisture content (MC) of 20.1 and 24.6 % dry-basis, respectively are studied using the circulating-bed technique. The inlet drying temperature is set as 45 and 55 °C including operation conditions of 1 stage and 2 stages circulating-bed drying. The inlet air velocity is fixed at 0.41 m/s and the grain mass flow rate of circulation is 0.23 kg/s. The desired final MC after drying of each experiment is in ranges of 16.5 - 16.8 % dry-basis. All of experimental data are non-linear regression analyzed by conventional drying equation models and the simulation results stated that the most suitable model for the circulating-bed drying of RD55 variety with inlet drying temperature of 45 and 55 °C is the Logarithmic and Approximation of diffusion model, respectively.

Keywords: Effective diffusion coefficient, Equilibrium moisture content, Mathematic drying modeling

Introduction

Rice staple has been an important economic crop of Thailand from the past to the present. Normally, fresh harvested paddy contains the moisture content around 18 - 26 % wet basis and fresh paddy might have high moisture content of paddy can be incident during harvesting in the rainy season period. It is realized that the post-harvesting management of highly moist paddy is a very serious problem in Asian countries because of high humidity surrounding conditions. The high humidity encourages the excessive mold growth and the high respiration rate from grain [1-3]. Consequently, the dry matter of the paddy grain kernel may also be lost and heat liberated from its respiration [4] and biological activities may accelerate rice yellowing [1-3]. The physical properties, chemical properties, biochemical properties and metabolic reactions occur during rice grain storage [5]. To obtain high quality of rice varieties and prevent all the problems mention above, some physical properties of paddy variety need to be studied such as equilibrium moisture content (EMC), effective diffusivity (D_{eff}), and specific heat capacity etc. However, the main principal parameter is the moisture content of paddy kernels because it relatively affects the degradation of grain kernels after post-harvesting period [1-7]. The safe moisture content of paddy for maintain high quality of paddy should be controlled between 15.0 and 16.0 % dry-basis [5,6]. Thus, the storage of each paddy variety requires a control of the moisture content of the paddy kernels to an appropriate level.

The equilibrium moisture content (EMC) value is moisture content of material which is in equilibrium state with surrounding temperature and relative humidity (RH). The EMC is an important parameter for post-harvesting processes such as drying and storage with surrounding temperature and RH [9]. At present, the determination of the EMC of various paddy varieties have been reported [1-3,10-12] and those of EMC are specific parameter which depends on its structure [1], composition such as grain kernel size, amount of amylose and amylopectin, its rice husk [10] and post-harvesting process for preparing of paddy such as pre-germination [8], parboiling [9]. There are many methods to determine the EMC value of paddy, however, the conventional method is the gravitational static method. This is because this static method is simple and has a high accuracy. The EMC value of GorKhor55 (RD55) and Hom Thammasat (HT) paddy varieties has not been reported and therefore it is necessary to evaluate the paddy characteristics, especially on drying kinetic modeling and storage which are carried out in this research. To obtain high quality of paddy and prevent all the problems mentioned above, the moisture content of the fresh paddy should be reduced and gentle drying is an essential technique for this purpose. The in-store paddy drying, which is well known as a fixed-bed drying, is the most common method. This drying technique always yields a good quality of milled rice because of its low drying temperature and low specific air flow rate. The evolution of moisture transfers from the grain kernel, some fruits and food have been evaluated by the unsteady liquid diffusion model based on Fick's second law of diffusion model. This diffusion model is widely used to determine the drying characteristics of paddy during drying [10]. The previous research works [5,6,9-11] proposed isothermal liquid diffusion models to describe the drying rate of grains kernel as a function of diffusivity. They also found that the effective diffusivity (D_{eff}) value depends on the inlet drying air temperature and initial moisture content.

Thus, the main objectives of this work were to evaluate various thermo-physical properties in terms of equilibrium moisture content (EMC) of GorKhor55 (RD55) and Hom Thammasat (HT) paddy varieties among surrounding temperatures of 40 - 60 °C and 0.11 - 0.88 of relative humidity. And the field experiment study of paddy drying with the circulating-bed drying techniques were carried on during rainy season. Finally, the effective diffusivity (D_{eff}) of these paddy varieties were determined.

Materials and methods

Materials

Two grain varieties of fresh organic GorKhor55 (RD55) and Hom Thammasat (HT) paddy were harvested and provided from Na Kaow-Plod-Pai group at Ban Nong-Tuy, Takria Tambol, Ranot District, Songkhla Province, Thailand. To remove any impurities and grain kernel immaturity, the fresh paddy samples were cleaned with an impurity separator prior to drying. And determination of moisture content of the paddy grain sample was followed using the standard AOAC method [10]. Initial moisture content of each fresh paddy sample was in ranges of 20 - 25 % dry-basis.

Methods

Evaluation of equilibrium moisture content (EMC)

The 5 saturated salt solutions for achieving an equilibrium moisture content values used in this experiments consists of LiCl, $Mg(NO_3)_26H_2O$, NaCl, KCl and KNO_3.These solutions provided surrounding relative humidity values of 10 - 90 % correlating to surrounding temperatures of 40 - 60 °C shown in **Table 1**.

Table 1 Saturated salt solutions provide the relative humidity values at surrounding temperatures of 40 - 60 °C [17].

Saturated salt solutions	Relative humidity (decimal) at different temperature		
	40 °C	50 °C	60 °C
LiCl	0.112	0.111	0.110
$Mg(NO_3)_26H_2O$	0.498	0.470	0.444
NaCl	0.747	0.743	0.745
KCl	0.823	0.812	0.803
KNO_3	0.878	0.849	0.811

Then the paddy samples were put in a stainless-steel basket hanging on each saturated salt solution and were sealed in airtight glass vials. Then each vial consisting of paddy sample and saturated salt solution were placed in an incubator at certain temperatures of 40, 50 and 60 °C to obtain final dry matter weight. When the paddy sample weight remained unchanged after 3 consecutive weight measurements (0.01 g) [5] the moisture content of paddy kernels was determined following the AOAC method [10]. The final moisture content of the paddy kernels sample implies the equilibrium moisture content (EMC) value, which occurred among static surrounding conditions.

The paddy sample weight was evaluated by triplication. Then, the conventional sorption isotherm models for predicting the EMC values were chosen to fit the experimental data are shown in **Table 2**.

Table 2 Mathematical model for prediction the equilibrium moisture content (EMC).

Name of model	EMC equation model	
Oswin [4]	$M_{eq} = A\left(\frac{RH}{(1-RH)}\right)^{B}$	(1)
Chung & Pfost [19]	$M_{eq} = (\frac{1}{B})ln\left(\frac{-A}{(RT)ln(RH)}\right)$	(2)
Modified Oswin [20,21]	$M_{eq} = (A+BT)\left(\frac{RH}{(1-RH)}\right)^{C}$	(3)
Modified GAB [21]	$M_{eq} = \left(\frac{AB(\frac{C}{T})(RH)}{(1-B(RH))(1-B(RH)+\left(\frac{C}{T}\right)B(RH)}\right)$	(4)
Modified Chung & Pfost [21]	$M_{eq} = \frac{1}{C}\ln\left(-\frac{A}{(T+B)\ln(RH)}\right)$	(5)

Note: RH is the relative humidity (decimal), M_{eq} is the equilibrium moisture content or EMC (% dry-basis), T is the temperature (K) and A, B, C are arbitrary coefficients of models.

The statistical principle for selecting the most suitable equation to describe the EMC process is the highest coefficient of determination value (R^2) and the lowest root mean square error (RMSE) value. The 2 statistic parameters can be calculated by Eqs. (6) and (7), respectively:

$$R^2 = 1 - \frac{\sum_{i=1}^{N}\left(X_{pi}-X_{ei}\right)^2}{\sum_{i=1}^{N}\left(X_{pi}-\overline{X}\right)^2} \tag{6}$$

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(X_{pi}-X_{ei}\right)^2} \tag{7}$$

where X_{pi} is the predicted value of data, X_{ei} is the experimental value of data, $\overline{X}$ is the mean of the experimental values and N is the number of experimental points.

Determination of moisture ratio

The moisture content at the beginning of the drying process and at equilibrium state was determined according to the standard AOAC method [10]. The drying curve is always drawn in terms of moisture ratio (*MR*) because this parameter can be used for comparative study with other paddy varieties. The moisture ratio (*MR*) is defined by the following Eq. (8):

$$MR = \frac{M_t - M_{eq}}{M_i - M_{eq}} \tag{8}$$

where M_{eq} is the equilibrium moisture content (decimal, dry-basis), M_i is the initial moisture content (decimal, dry-basis), M_t is the moisture content at time t (decimal, dry-basis).

Drying experimental set-up

For the paddy drying experiment with the circulating-bed type dryer (capacity of ≤ 2 tons/batch), it consists of a heat source using liquefied petroleum gas (LPG) stove, a control unit including temperature control and electricity control, a 2.0 hp centrifugal blower, screw conveyor and bucket conveyor section. The drying temperature is controlled by using a thermostat to operate a solenoid valve to supply LPG to the stove. The solenoid valve shuts off when the temperature inside the drying chamber is exceeded and opens when the temperature drops. The non-fragrant RD55 and fragrant HT paddy variety was dried at drying temperature between 40 and 60 °C while the inlet air velocity is fixed at 0.43 m/s and the paddy grain kernel with the circulating rate of 0.23 kg/s. Each drying process will be carried on and be stopped when the average final moisture content of the sample reaches to 15 - 16 % dry-basis [1,3]. All of the experimental set-up conditions are illustrated in **Table 3**.

Table 3 The 2 paddy varieties drying conditions with circulating-bed dryer.

Paddy variety	Sample weight (kg)	Drying temperature (°C)	Air velocity (m/s)	Grain flow rate (kg/s)
GorKhor55(RD 55)	500	45	0.43	0.23
GorKhor55 (RD 55)	1,130	55	0.43	0.23
Hom Thammasat	1,325	2-stages (40 and 55)	0.43	0.23
Hom Thammasat	751	55	0.43	0.23

Note: 2-stages is the experiment using air temperature 40 °C for 8 h then using air temperature of 55 °C for 5 h.

Evaluation of drying kinetics and mathematical drying modeling

Relationship between the moisture ratios (*MR*) and drying time shows the drying kinetics of the sample during the drying process. The evolution of moisture transfer can be analyzed by 3 major mathematical drying modeling as follows: (a) Mathematical simulation including heat and mass transfer balance, (b) the diffusion model following the second Fick's law of diffusion, and (c) the empirical drying model [4]. The first and second modeling are analytically solved by complicated mathematical methods whilst the empirical model is quite suitable for the experimental data but it has limited usage.

Simulation of empirical drying model

The drying experimental data of the 2 paddy varieties were analyzed by using the 9 conventional empirical drying models as illustrated in **Table 4**. The highest R^2 and the lowest RMSE value were used as the principal criteria for selecting the most suitable drying model to describe the evolution of exact experimental data.

Table 4 Mathematical drying models for prediction drying kinetics behavior.

Drying kinetic model	Equation	
Newton [22,29]	$MR=\exp(-kt)$	(9)
Page [24,25,29]	$MR=\exp(-kt^n)$	(10)
Modified Page [24,25,29]	$MR=\exp(-kt)^n$	(11)
Logistic [25]	$MR=\frac{a}{(1+\exp(kt))}$	(12)
Henderson and Pabis [25,26,29]	$MR=a\exp(-kt)$	(13)
Logarithmic [25,29]	$MR=a\exp(-kt)+c$	(14)

Drying kinetic model	Equation	
Two term exponential [25,27,29]	MR=aexp(-kt)+(1-a)exp(-kat)	(15)
Approximation of diffusion [25,28,29]	MR=aexp(-kt)+(1-a)exp(-kbt)	(16)
Verma *et al*. [25,30]	MR=aexp(-kt)+(1-a)exp(-gt)	(17)

Note: a, b, c, k and n are arbitrary constants of drying kinetic model, t is drying time (h).

Determination of effective diffusion coefficient **(**D_{eff} **)**

Drying of many biomaterial products has also been successfully predicted using the second Fick's law of diffusion [6,9,11,12]. Assumption is based on the water content diffuses through the sample structure with constant water diffusion rate and uniform initial moisture content whilst the effect of volume change, shrinkage, and external resistance is negligible [11]. Therefore, the diffusion equation of the Fick's law for finite cylindrical shape was applied and the diffusion equation can be solved in the general solution as the following Eq. (18) below:

$$MR = \left\{ \left(\frac{8}{\pi^2}\right) \sum_{p=0}^{\infty} \left(\frac{1}{(2p+1)^2}\right) \exp\left(-\frac{(2p+1)^2 \pi^2 D_{eff} t}{L^2}\right) \right\} \times \left\{ \sum_{n=1}^{\infty} \left(\frac{4}{\lambda_n^2}\right) \exp\left(-\frac{\lambda_n^2 D_{eff} t}{4 r_0^2}\right) \right\} \tag{18}$$

where D_{eff} is the effective diffusivity (m^2/s), t is drying time (s), r_0 is the average radius of the paddy kernel (m), λ_n is order of the root of Bessel function (λ_1 = 2.4048, λ_2 = 5.5201, λ_3 = 8.6537), and L is the length of the paddy kernel (m).

If we consider only p = (1, 2) and n = (0, 1), then the extension terms of following Eq. (18) can be written as Eq. (19) below:

$$\begin{aligned} MR &= 0.5619 \exp(-5.7802\, N_{Fi} - 2.4649\, N_{Fio}) + 0.0623 \exp(-5.7802\, N_{Fi} - 22.207\, N_{FO}) \\ &+ 0.1064 \exp(-30.47\, N_{Fi} - 2.4649\, N_{FO}) \end{aligned} \tag{19}$$

where N_{Fi} is Fick number, $\frac{D_{eff}t}{R^2}$, and N_{Fo} is Fourier number, $\frac{D_{eff}t}{L^2}$.

By following the previous work [12,13], the first term of Eq. (19) is much greater than the latter 3 terms. So, the first term could only be considered, then the resulting in the natural log of Eq. (19) can be written as:

$$\ln(MR) = \ln(0.5619) - \left(\frac{5.7802}{R^2} + \frac{2.4649}{L^2}\right) D_{eff} t \tag{20}$$

To determine the effective moisture diffusivity (D_{eff}) using Eq. (20), the logarithmic graph between MR and t has been plotted. So, the slope of this linear graph was evaluated and the effective diffusivity of paddy variety was determined. In this case, the slope can be obtained from the graph by plotting between ln (MR) value in the y-axis and the drying time in the x-axis. Therefore, the effective diffusivity can be determined using Eq. (21).

$$D_{eff} = -\frac{Slope}{\left(\frac{5.7802}{R^2} + \frac{2.4649}{L^2}\right)} \tag{21}$$

where D_{eff} is effective moisture diffusivity (m^2/s) and R is the radius of the paddy kernel (m) with 0.00096 m and 0.00098 m for RD55 and HT paddy variety, respectively. L is the grain length (m) with 0.00966 and 0.00934 m for RD55 and HT paddy variety, respectively.

Results and discussion

Determination of equilibrium moisture content (EMC)

From the experimental set-up, the experimental data of the EMC value of the RD55 and HT paddy varieties were determined by following the standard AOAC method for a surrounding temperature ranging of 40 - 60 °C which correlated to the relative humidity (RH) ranging from 10 to 90 %. These experimental values were statistically analyzed by non-linear regression methods. The best fitted coefficients of the EMC equations were simulated and shown in **Tables 5 - 6**. The results showed that the simulated results using the Modified Oswin model have a good relationship to the experimental results of both paddy varieties (the highest R^2 value and the lowest RMSE). From the experimental results, the conclusion of the study of the EMC value of RD55 and HT paddy states that at the constant temperature the EMC value depends on the relative humidity of air surrounding. When the surrounding relative humidity decreases, the EMC value of fragrant and non-fragrant paddy varieties decreases, respectively. This is because the water vapor transfer between surrounding air and paddy grain kernels is high at the low surrounding relative humidity. On the other hand, at the constant relative humidity, the EMC value is relatively dependent on the surrounding temperature. This is because the heat reduces the binding force in the water molecules. All of the water vapor transfer mechanism between paddy grain kernels and surrounding air is corresponded to the other previous works which were reported on EMC values of different paddy varieties such as Suphanburi1 and IR1010 paddy varieties [6,7,25].

Table 5 Arbitrary constant of EMC models for Gorkhor55 (RD55) paddy in relative humidity ranging of 10 - 90 %.

Model	**Arbitrary constants**			**R^2**	**RMSE**
	A	**B**	**C**		
Oswin [18]	0.0733	0.4739	-	0.9781	0.0077
Chung & Pfost [15]	8873.5757	18.8959	-	0.9601	0.0103
Modified Oswin [20, 21]	0.2255	−0.0005	2.2015	0.9906	0.0050
Modified GAB [21]	3686.1152	0.2847	0.0334	0.9501	0.0116
Modified Chung & Pfost [21]	180.3588	–269.3444	19.1411	0.9767	0.0079

Table 6 Arbitrary constant of EMC models for Hom Thammasat (HT) paddy variety in relative humidity ranging of 10 - 90 %.

Model	**Arbitrary constants**			**R^2**	**RMSE**
	A	**B**	**C**		
Oswin [18]	0.083935	0.419704	-	0.9799	0.0073
Chung & Pfost [19]	18.75	10228.95	-	0.9737	0.0084
Modified Oswin [20,21]	0.210903	–0.000390	2.446899	0.9879	0.0057
Modified GAB [21]	3154.340	0.113	0.144	0.9487	0.0117
Modified Chung & Pfost [21]	280.956	–250.324	18.913	0.9815	0.0070

Mathematical drying kinetics modeling

Finally, the experimental data of all drying conditions were analyzed with the 9 drying kinetic models as presented in **Table 4**. The arbitrary constant values of each model were determined by non-linear regression method and were shown in **Tables 7 - 8**. The selection of the most suitable drying kinetics model was based on the criteria of the highest coefficient of determination value (R^2) and the lowest root mean square error (RMSE) value. From the simulation results of **Tables 7 - 8**, the conclusions were that the best curve fitting model for the GorKhor55 (RD55) paddy variety (non-fragrant rice) at the drying temperature of 45 °C and drying temperature of 55 °C are the Logarithmic model and the Approximation of diffusion model, respectively. However, the drying kinetics models for the GorKhor55

(RD55) paddy variety with drying temperature between 45 and 55 °C can be evaluated only by the Approximation of diffusion model. This is because the R^2 and RMSE value of the Logarithmic model is slightly different from the Approximation of diffusion model as shown in **Table 7**. For HT fragrant paddy variety drying with 1 stage and 2-stages drying as illustrated in **Table 8**, the empirical drying kinetics simulation was stated that the best curve fitting for the experimental data of HT paddy with the 1 stage and 2-stages drying is the Approximation of diffusion model. These empirical drying kinetics modeling results showed that the limitation of empirical drying model developed form the experimental data under their drying condition can only be used for these conditions. It is corresponded to the previous works [16,25,26].

Table 7 Empirical constant and some statistical parameters obtained of drying models by non-linear regression analysis for GorKhor55 (RD55) non-fragrant paddy drying.

Model	Arbitrary constants	R^2	RMSE
Circulating bed drying at drying temperature of 45 °C			
Newton [22,29]	k = 0.12077	0.92385	0.02199
Page [24,25,29]	k = 0.15026, n = 0.64130	0.99244	0.00693
Modified Page [24,25,29]	k = 0.363149, n = 0.332554	0.92385	0.02199
Logistic [25]	k = 0.18964, a = 1.94352	0.93470	0.02036
Henderson and Pabis [25,26,29]	k = 0.10698, a = 0.97648	0.94875	0.01804
Logarithmic [25,29]	k = 0.75276, a = 0.27257, c = 0.72819	**0.99775**	**0.00378**
Two term exponential [25,27,29]	k = 1.64354, a = 0.05598	0.97608	0.01232
Approximation of diffusion [25,28,29]	k = 0.75261, a = 0.26970, b = 0.00130	0.99773	0.00380
Newton [22,29]	k = 0.75261, a = 0.26970, g = 0.00099	0.99743	0.00378
Circulating-bed drying at drying temperature of 55 °C			
Newton [22,29]	k = 0.06932	0.92922	0.01835
Page [24,25,29]	k = 0.09638, n = 0.68718	0.98912	0.00719
Modified Page [24,25,29]	k = 0.17676, n = 0.39217	0.92922	0.01835
Logistic [25]	k = 0.10873, a = 1.94588	0.94740	0.01581
Henderson and Pabis [25,26,29]	k = 0.06068, a = 0.97706	0.95836	0.01407
Logarithmic [25,29]	k = 0.40090, a = 0.26721, c = 0.73154	0.99360	0.00552
Two term exponential [25,27,29]	k = 1.01611, a = 0.05156	0.97829	0.01016
Approximation of diffusion [25,28,29]	k = 0.19542, a = 0.68358, b = –0.52083	**0.99405**	**0.00532**
Newton [22,29]	k = 0.06932, a = –36.04239, g = 0.06932	0.92922	0.01835

Table 8 Empirical constant and some statistical parameters obtained of drying models by non-linear regression analysis for Hom Thammasat (HT) fragrant paddy drying.

Empirical drying model	Arbitrary constants	R^2	RMSE
2-stages circulating-bed drying at drying temperature of 40 and 55 °C			
Page	k = 0.04332×exp(362.95884/T) n = 0.43927	0.97782	0.01327
Logistic	k = 0.00003×exp(2379.04328/T) a = 1.84128	0.87364	0.03167
Logarithmic	k = 0.03335×exp(700.82925/T) a = 0.30274 c = 0.67909	0.95315	0.01928
Two term exponential	k = 0.00010×exp(2736.28562/T) a = 0.06771	0.88006	0.03086
Approximation of diffusion	k = 0.17006×exp(-528.13739/T) a = 0.176 b = 0.019	**0.98444**	**0.01111**
circulating-bed drying at drying temperature of 55 °C			
Newton	k = 0.08782	0.91571	0.03445
Page	k = 0.15085, n = 0.62277	0.99744	0.00600
Modified Page	k = 0.31637, n = 0.27760	0.91571	0.03445
Logistic	k = 0.12757, a = 1.89121	0.93058	0.03127

Empirical drying model	Arbitrary constants	R^2	RMSE
Henderson and Pabis	k = 0.07636, a = 0.95641	0.95014	0.02650
circulating-bed drying at drying temperature of 55 °C			
Logarithmic	k = 0.34736, a = 0.40347, c = 0.59057	0.99306	0.00988
Two term exponential	k = 0.86165, a = 0.08015	0.97382	0.01920
Approximation of diffusion	k = 1.06215, a = 0.14565, b = 0.04760	**0.99824**	**0.00499**
Verma *et al.*	k = 0.08782, a = 28.02693, g = 0.08782	0.91571	0.03445

Note: 2 Stages is the experiment using air temperature 40 °C for 8 h then using air temperature 55 °C for 5 h and T is drying temperature (K).

The comparison of the experimental data and predicted data of moisture ratio (*MR*) of Gorkhor55 (RD55) and HT paddy drying at temperatures of 40 - 60 °C was presented as shown in **Figures 3 - 4**. From the experiment, the evolution of moisture transfers of RD55 paddy using circulating-bed drying at temperature of 45 °C was slightly high compared to the drying with high temperature of 55 °C. This is because the mass of paddy drying at 45 °C (500 kg) is lower than the mass of paddy drying with 55 °C (1,130 kg), so the recirculating rate of paddy mass at low temperature is faster than the drying experiment at high temperature. It implied the heat and moisture transfer of the low amount of sample mass with the circulating-bed drying is higher than the high amount of sample mass. However, if the mass of fresh paddy is fixed in each experiment, the decreasing of the moisture ratio of paddy drying with the higher temperature must be faster than the drying with the lower temperature [3,23,26].

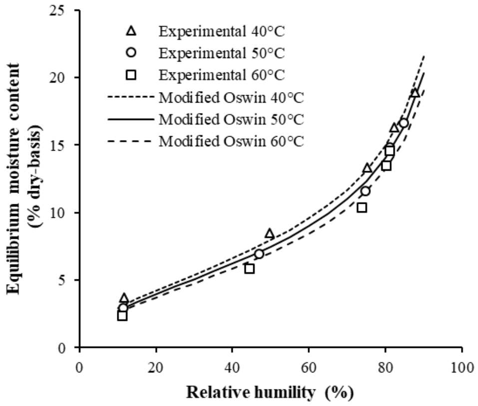

Figure 1 Comparison of the experimental data (dot) and predicted data (line) of the equilibrium moisture content models of RD55 rice variety among surrounding relative humidity and surrounding temperature of 10 - 90 % and of 40 - 60 °C, respectively.

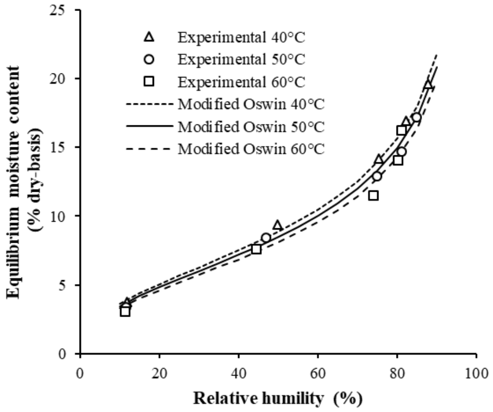

Figure 2 Comparison of the experimental data (dot) and predicted data (line) of the equilibrium moisture content of HT fragrant paddy variety among surrounding relative humidity and surrounding temperature of 10 - 90 % and of 40 - 60 °C, respectively.

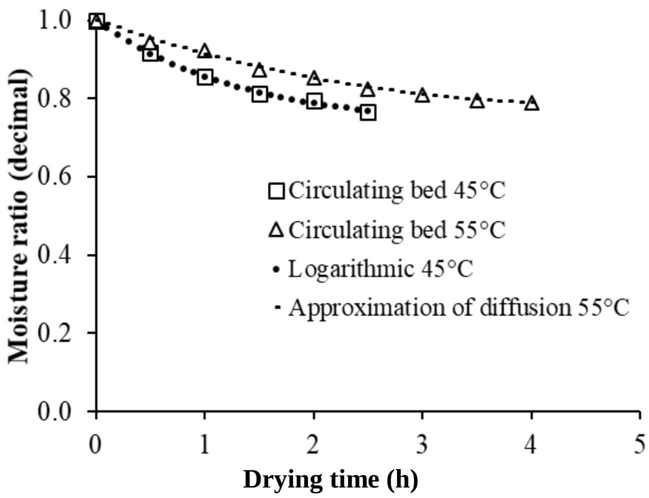

Figure 3 Comparison of the experimental data (dot) and predicted data (line) of moisture ratio of 1 stage RD55 non-fragrant paddy drying at temperatures of 45 and 55 °C.

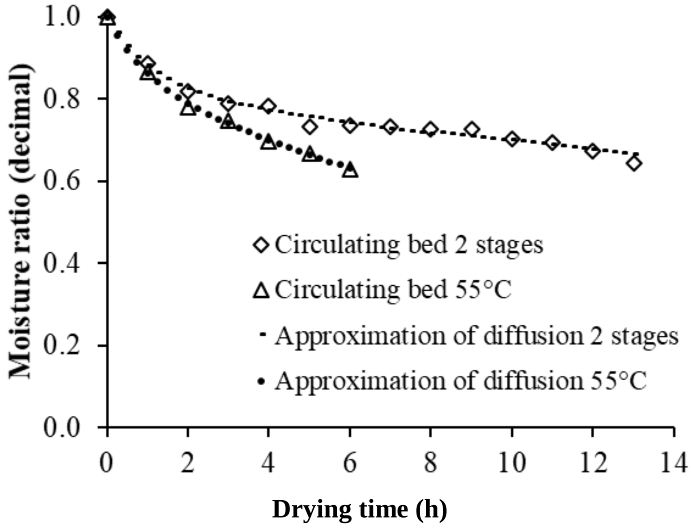

Figure 4 Comparison of the experimental data (dot) and predicted data (line) of moisture ratio for HT fragrant paddy drying at temperatures of 40 - 60 °C.

Determination of effective diffusion coefficient (D_{eff})

Additionally, to study drying kinetics mechanism by semi-theoretical drying model, the effective diffusion coefficient (D_{eff}) value of both paddy varieties was simulated by following the Fick's law of diffusion and the D_{eff} values were presented in **Table 9**. The results stated that the RD55 paddy variety dried with the drying temperature of 45 °C was higher D_{eff} than that of the RD55 paddy variety drying with drying temperature of 55 °C. This may because the amount of RD55 paddy drying with lower temperature of 45 °C was 500 kg whilst the RD55 paddy drying with the higher temperature of 55 °C was about 1,130 kg. So, the RD55 variety drying with 45 °C can be circulated to the drying zone of the dryer faster than the experiment with 55 °C.

Table 9 Effective diffusion coefficient value of the 2 paddy varieties in each circulating-bed drying condition.

Paddy variety	L (mm)	R (mm)	Drying temperature (°C)		Sample weight (kg)	Initial moisture content (% d.b.)	D_{eff} ($\times 10^{-10}$ m^2/min)
GorKhor55 RD55	9.66	0.96	45		500	20.3	3.182
GorKhor55 RD55	9.66	0.96	55		1,130	20.3	3.750
Hom Thammasat HT	9.34	0.98	2-stages	40(8h)	1,325	24.5	4.939
				55(5h)			2.752
Hom Thammasat HT	9.34	0.98	55		751	24.7	8.294

Note: L is the half length of a cylinder and R is the radius of the paddy kernel.

For study of the 2-stages drying of the HT paddy variety of 2,500 kg, the experiment was carried out at rainy season period in the South part of Thailand (October-January) and the initial moisture content of the fresh HT paddy variety was around 28 % dry-basis. At the beginning of the first 8 h of 40 °C drying, the moisture content of the HT paddy decreased rapidly during the first drying period of 4 h. This is because the moisture content of paddy surface is high and is easily transferred to air at drying zone of the circulating-bed dryer. During 4 to 8 h of the drying experiment, the evolution of moisture transfer was slightly slow decreased. In addition, the D_{eff} value was relatively high because the drying phenomena remained on the surface of the paddy grain kernel. The high amount of free bound water content nearby paddy kernels surface was easier to transfer than the free bound water content inside the paddy kernels. However, during doing experiment the rice agriculture cooperative requested us to hurry up drying because they have > 700 kg of fresh HT paddy with high moisture content which waited for drying. To avoid loss of the physical properties and degradation of fresh paddy such as the yellowing, grain kernel fatigue and low head rice yield [1-5], the second stage has been done on drying temperature of 55 °C of the rest of drying time. So after 8-drying h, the drying temperature of this experiment has been changed from 40 to 55 °C. So, the D_{eff} value of the HT paddy variety was relatively low compared to the first 8 drying h. This low D_{eff} of the HT paddy variety sample dried with 55 °C might be because the moisture content of HT paddy was lower than the moisture content of HT paddy during the first stage of drying and free bounded water content inside the grain kernels were hardly moved to the grain kernel surface. The D_{eff} values were evaluated for both GorKhor55(RD55) and HT paddy varieties were in the ranges of 3.182 – 3.750$\times 10^{-10}$ m^2/min and 2.752 – 8.294$\times 10^{-10}$ m^2/min, respectively. The D_{eff} values were in the same range as the previous works [6]. The effective diffusivity value of non-fragrant and fragrant rice variety has no difference.

Conclusions

Determination of the equilibrium moisture content (EMC) is a principal physical parameter of grain kernel because it can help us to preparation the suitable surrounding condition for grain kernel during storage and shelf-life duration. The conclusion states that the EMC value of both paddy varieties has the same trend even they are different in grain size and type of rice. Additionally, the EMC value of non-fragrant (GorKhor55 (RD55)) and fragrant (HT) paddy varieties relatively depends on the surrounding temperature and relative humidity. The simulation modeling of water sorption isotherms carried out and indicated that the Modified Oswin model has the supremacy in prediction of equilibrium moisture content of the GorKhor 55 (RD55) and Hom Thammasart (HT) paddy varieties.

In field experiment of paddy drying in rainy season, drying of high initial moisture content of fresh paddy by hot air and recirculating-bed technique stated that the suitable drying temperature to reduce water content by without grain degradation should be in range of 45 - 55 °C. To determine the drying kinetics modeling of paddy varieties, the conclusion states that the Approximation of diffusion model has a good relation to the experimental results of RD55 and HT. And the Logarithmic model also has a good agreement with the experimental results of RD55 at drying temperature 45 °C. Finally, for the circulating-bed drying experiment, the conclusion is that the drying rate and the effective diffusion coefficient (D_{eff}) value of both paddy varieties are dependent on their grain size, relative humidity and drying temperature.

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