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Original Article

Effective moisture diffusivity, moisture sorption, thermo-physical properties and infrared drying kinetics of germinated paddy

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Abstract

Temperature and relative humidity (RH) dependence of moisture sorption phenomena for agricultural products provide valuable information related to the thermodynamics of the system. So the equilibrium moisture contents (EMC), effective moisture diffusivity (D_{eff}) and thermo-physical properties in terms of void fraction, specific heat capacity, and the apparent density of germinated non-waxy Suphanburi 1 paddy were evaluated. Five commonly cited EMC equations were fitted to the experimental data among temperatures of 40-60°C correlating with RH of 0-90%. The results showed that the modified GAB equation was the best function for describing experimental results while those evaluated thermo-physical properties depended on moisture content. To determine drying kinetics model, the simulated values using Midilli *et al.* (2002) model and Page's model was the best fitting to exact drying kinetics values for infrared (IR) and hot air (HA) drying, respectively. Finally, the D_{eff} value of paddy dried with IR and HA sources were also evaluated and the calculated D_{eff} value of both HA and IR drying was in order of 10^{-9} m^2/s.

Keywords: GABA rice, drying modeling, effective diffusivity, long-grain rice, thermo-physical properties

1. Introduction

Rice (*Oryza sativa L.*) is staple cereal grain and is easily planted in every continent, especially in the tropical zone. Rice varieties in Thailand have over 5,900 varieties (Banchuen *et al.*, 2005) and one of the foremost rice varieties is the fragrant Khao Dawk Mali 105 (KDML 105) rice variety (low amylose content), which is mainly produced in the Northern and Northeastern part of Thailand. On the other hand, most of the non-glutinous paddy varieties that are produced in the Southern and Central part of Thailand are preferred. The texture of some non-glutinous rice varieties are slightly harder compared to KDML105 rice even if the physical qualities of the rice grain kernel are not much different (Ngamchuen *et al.*, 1985; Tirawanichakul *et al.*, 2004). However, the chemical and physicochemical qualities of the rice varieties are quite different (Ngamchuen *et al.*, 1985), especially on post-harvest treatment, such as drying process (Donludee *et al.*, 2008; Tirawanichakul *et al.*, 2004), heat treatment (Champagne, 1994; Soponronnarit, 1997; Donludee *et al.*, 2008; Soponronnarit *et al.*, 2008) and storage conditions (Ohata *et al.*, 1990; Teten *et al.*, 1997; Tirawanichakul *et al.*, 2004). One of post-harvest treatment processes that can maintain the quality of the rice and add value to the rice is the parboiling technique. The rice parboiling process namely involves soaking paddy in cold water (or hot water) and then steamed at variable pressures, followed by drying and finally milling. The parboiled rice is a good grain kernel of dietary fibres, essential amino acids, proteins, carbohydrates, vitamins and others (Jannoey *et al.*, 2010). In addition,

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previous researches also referred high nutritious content in some special rice such as brown rice, germinated rice, and γ-aminobutyric acid (GABA) rice, which were prepared in form of parboiled rice (Rashmi and Urooj, 2003; Donludee *et al.*, 2008). It has been stressed out that parboiled rice presents a superior nutritional value in relation to milled rice, mainly due to the retention of minerals and water-soluble vitamins (Juliano, 1985; Nunes *et al.*, 1991; Verschuren, 2002). Parboiling also results in a less insect-infested product and causes hardening of the grains, which makes them more resistant to breakage during milling (Bhattacharya, 1985; Juliano, 1985; Sajwan *et al.*, 1990; Soponronnarit *et al.*, 2008). However, brown rice is slightly harder, has low stickiness and crumbly texture compared to GABA rice. The GABA content in parboiled rice and germinated rice kernels plays an important role in the central nervous system as a neurotransmitter. The rice kernel with GABA content is a good product for conferring a health benefit (Shoichi, 2004), food diet, inhibited cancer cell proliferation (Oh and Oh, 2004; Komatsuzaki *et al.*, 2007), especially on germinated mature paddy (Banchuen *et al.*, 2009; Jannoey *et al.*, 2010). Chung *et al.* (2009) reported the GABA content of barley increased with increasing germination time and was higher in the buffer solution (pH 6.0, 50 mmol/L sodium acetate) than water. Moreover, Kim *et al.* (2012) concluded that the changes in chemical and functional components in different parts of rough rice kernels before and after germination. They found that the GABA content showed the highest increase from 15.34 to 31.79 mg/100 g in the rough rice part after germination. Unfortunately, there are a few research studies concerning the thermo-physical properties and diffusion phenomena of germinated rice during heat treatment. One of important parameters of the paddy during post-harvesting period is the equilibrium moisture content (EMC). The EMC is expressed as the moisture content at which the internal product vapor pressure is in equilibrium with the vapor pressure of the environment (Halsey, 1948; Henderson, 1952; Henderson and Pabis, 1961; Chung and Pfost, 1967; Chen, 1990; Soponronnarit, 1997; Kaya and Kahyaoglu, 2005; Smith *et al.*, 2006). The EMC value of grain kernel depends on temperature and relative humidity surrounding and grain species (Juliano, 1985; Bhattacharya, 1985; Soponronnarit, 1997; Tirawanichakul *et al.*, 2004; Tirawanichakul *et al.*, 2007; Tirawanichakul *et al.*, 2008; Banchuen *et al.*, 2009; Bualuang *et al.*, 2011). It determines the minimum moisture content to which the grain can be approached under a given set of drying and storage conditions. So, the EMC of germinated paddy should be studied.

It is generally agreed that the moisture reduction from the grain kernel, some fruits and food such as rough rice, corn, fish, starch, is described by the unsteady liquid diffusion model based on Fick's law (Henderson and Pabis, 1961). Crank (1975) previously proposed isothermal liquid diffusion models to describe the drying rate of a grain as a function of diffusivity. Additionally they found that the effective diffusivity (D_{eff}) value depends on the inlet drying air temperature and initial moisture content, especially on infrared drying. However, only a few research studies on the application of moisture removal for germinated paddy variety have been reported and studied.

Thus, the main objectives of this work were to evaluate various thermo-physical properties in terms of equilibrium moisture content (EMC), apparent density (r), void fraction (e), specific heat capacity (c_p) and effective diffusivity (D_{eff}) of high amylose germinated paddy cultivar. The drying kinetics of germinated paddy was also carried out under the conditions of infrared radiation and hot air convection techniques.

2. Materials and Methods

Fresh paddy of Suphanburi 1 (SP 1) variety was provided by the Rice Research Institute at Phatthalung Province, Thailand. The fresh paddy was cleaned in water to remove immature grains and impurities. Then the mature SP 1 paddy samples were pre-germinated by soaking in tap water at room temperature for 24-48 hrs and replacing the soaked water with draining and rinsing every four soaking hours. During this soaking time, the rice kernel germination was evident with endosperm germination of 1-2 mm length (germinated rice). Then, the germinated paddy kernels were steamed at 95±5°C for 30 min. Then the germinated paddy samples were placed in ambient air surrounding for 3 hrs before drying by following of Varanyanond *et al.* (2005). Determination of moisture content of the paddy grain was followed using the AOAC method (AOAC, 1995). Initial moisture content of germinated SP 1 paddy samples was in the range of 47-50% dry-basis.

2.1 Methodology

2.1.1 Determination of equilibrium moisture content

Four saturated salt solutions which were used for achieving an equilibrium moisture content stage in the experiments consisted of LiCl, $MgCl_2{\bullet}6H_2O$, $Mg(NO_3)_2{\bullet}6H_2O$ and NaCl solution. These four salt solutions provide the surrounding relative humidity of 10-90% correlating to the surrounding temperatures of 40-60°C (Tirawanichakul *et al.*, 2007). Each weighed paddy sample was put in a stainless steel basket hanging on one of the four saturated salt solutions in an airtight vial. These surrounding conditions cover all drying conditions because of providing the equilibrium moisture content ranging of 0.5-100% dry-basis (Henderson, 1952; Chung and Pfost, 1967; Iglesias and Chirife, 1976; Pfost *et al.*, 1976; Bala, 1997; Soponronnarit, 1997; Tirawanichakul *et al.*, 2008). The moisture content was determined when the sample weight remained unchanged after three consecutive weight measurements (0.01 g). The samples were then, following the AOAC method (AOAC, 1995), taken and weighed to determine the final moisture content (so-called equilibrium moisture content, M_{eq}). The final dry matter weight can then be calculated. The sample weights were evaluated in triplicates. Isotherm models for predicting EMC values, chosen for fitting of the experimental data, are shown in Table 1.

The EMC value was mostly formulated as a function of temperature and relative humidity. The arbitrary constants in all EMC equations (in Table 1) were determined using the non-linear regression analysis. The coefficient of determination (R^2) and root mean square error (RMSE) values were used as the primary criteria for selecting the best equation to describe the experimental data and are defined in Equation 1 and 2.

$$R^2 = 1 - \frac{\Sigma_{i=1}^{N}\left(X_{p,i} - X_{e,i}\right)^2}{\Sigma_{i=1}^{N}\left(X_{p,i} - \bar{X}\right)^2} \tag{1}$$

$$RMSE = \left[\frac{1}{N}\Sigma_{i=1}^{N}\left(X_{p,i} - X_{e,i}\right)^2\right]^{1/2} \tag{2}$$

where $X_{p,i}$ is the predicted value of data, $X_{e,i}$ is the experimental value of data, $\bar{X}$ is the average of the experimental values, N is the number of experimental points. These EMC values for germinated SP 1 paddy variety will be used in evaluation of moisture ratios of empirical drying model simulation which was presented in the next Section 2.1.5.

2.1.2 Apparent density

Apparent density (ρ) of germinated Suphanburi 1 rice was determined within the initial moisture content ranges of 13-47% dry-basis. Each grain sample was placed fully in a 50 ml volumetric flask. The mass of samples was weighed by an electronic balance with an accuracy of ±0.01 grams. The mean moisture content was presented by means of five replications for each moisture contents. Then the apparent density is calculated by dividing the mass with the bulk volume as shown in Equation 8.

$$\rho = \frac{m}{V_b} \tag{8}$$

where ρ is apparent density of germinated paddy kernel (kg/m^3), m is mass of the rice kernel samples (kg) and V_b is volume of the volumetric vessel (m^3). An average value of apparent density was calculated by means of triplication.

2.1.3 Percentage of void fraction

The percentage of void fraction (ε) of samples is normally defined as the fraction of the space in its bulk volume (Soponronnarit, 1997; Komatsuzaki *et al.*, 2007; Tirawanichakul *et al.*, 2008). The following equation for percentage of void fraction of germinated SP 1 paddy variety was evaluated as below.

$$\%\varepsilon = \frac{V_{oil}}{V_b} \times 100 \tag{9}$$

where ε is percentage of void fraction (%), V_{oil} (m^3) and V_b is oil volume and vessel volume in m^3, respectively. An average percentage value of void fraction was calculated by means of triplication.

Table 1. Five commonly mathematical models for prediction equilibrium moisture content of germinated Suphanburi 1 rice variety (adapted from Soponronnarit, 1997; Tirawanichakul *et al.*, 2008).

Model name	Equilibrium moisture content equation	Equation no.
Oswin (1946)	$M_{eq} = A\left[\frac{RH}{(1-RH)}\right]^B$	(3)
Henderson (1952)	$M_{eq} = \left[\frac{-\ln(1-RH)}{A(T+273.15)}\right]^{1/B}$	(4)
Smith (1948)	$M_{eq} = A + B\ln(1-RH)$	(5)
Modified Oswin (1946)	$M_{eq} = (A + B(T+273.15))\left[\frac{RH}{(1-RH)}\right]^C$	(6)
Modified GAB (1985)	$M_{eq} = \frac{AB(\frac{C}{(T+273.15)})RH}{[1-B(RH)][1-B(RH)+(\frac{C}{(T+273.15)})B(RH)]}$	(7)

2.1.4 Specific heat capacity

The specific heat capacity (c_p) of germinated SP 1 rice was evaluated among moisture content ranging of 13-47% dry-basis. Fifty grams of germinated rice samples were placed into a bomb calorimeter. Forty grams of tepid distilled water (65°C) was added into the calorimeter and mixed thoroughly. An equilibrium temperature value was then recorded. Five repetitions for each sample were carried out at the same conditions. Specific heat capacity of the germinated Suphanburi 1 rice was determined according to the following equation, Equation 10.

$$c_p = \frac{\left[-m_c c_c \left(T_{eq} - T_c\right) - m_w c_w \left(T_{eq} - T_w\right)\right]}{m_p \left(T_{eq} - T_p\right)} \quad (10)$$

where c_p is the specific heat capacity of the germinated paddy, c_c is the specific heat capacity of the calorimeter, c_w is the specific heat capacity water, m_c is the mass of the calorimeter, m_w is the mass of water, m_p is the mass of the germinated rice, T_{eq} is the equilibrium temperature, T_c is the initial temperature of the calorimeter, T_w is the initial temperature of water, and T_p is the initial temperature of germinated rice. The units for the specific heat capacity, the mass and the temperature in the equation are kJ/kg°C, kg and °C, respectively.

2.1.5 Determination of drying kinetics model and effective diffusion coefficient

To study the drying kinetics of germinated SP 1 paddy, the sample with initial moisture content ranging of 47-50 % dry-basis were provided. The germinated paddy samples were thin-layer dried with infrared radiation 1,000 W (IR) and hot air (HA) under the conditions of drying temperatures of 60-100°C and inlet air velocity of 1.1±0.2 m/s. The drying air temperature was precisely controlled by a PID controller with an accuracy of ±0.5°C. The sample was continuous weighed by using electronic balance with an accuracy of ±0.1 g. The drying experiments were over when the final moisture content reached 14-16% dry-basis (Soponronnarit, 1997; Tirawanichakul *et al.*, 2004). Then the experimental data were used for simulation by using empirical drying models in-layer drying models that describe the drying phenomenon of these materials mainly fall into three categories: empirical, theoretical, and semi-theoretical (Abalone *et al.*, 2006). The first two predictions have been employed in this study.

1) Empirical drying model

The moisture content of the germinated rice during the thin-layer drying experiment can be calculated from the Equation 11.

$$MR = \frac{\left(M_t - M_{eq}\right)}{\left(M_{in} - M_{eq}\right)} \quad (11)$$

where MR is the moisture ratio (dimensionless), M_{in} is the initial moisture content of the germinated rice (dry-basis), M_t is the moisture content at time t (dry-basis) and M_{eq} is the equilibrium moisture content (dry-basis), all in decimal. The EMC value was determined by the good fitting equation from the Section 2.1.1. The experimental data for prediction drying kinetics of paddy samples were analyzed by using five conventional empirical models as illustrated in Table 2. The highest R^2 and the lowest RMSE value were used as the principal criteria for selecting the best drying model to describe the experimental data.

2) Semi-theoretical model

Theoretical drying equation is based on the moisture diffusion process. Drying of many food products has also been successfully predicted using Fick's law of diffusion. Assumption is that water content diffuses through the grain kernel with constant water diffusion rate and the effect of volume change is negligible. Additionally, the surface concentration of grain kernels reaches saturation instantaneously upon water immersion (Crank, 1975). Thus the Fick's law of diffusion in terms of the average moisture content (MR) can be used for prediction of the falling drying rate period. In this case, the shape of paddy kernel was in a form of short cylindrical shape (finite cylinder) and the following equation of analytical solution for the moisture inside a single kernel is expressed as Equation 17:

Table 2. Five mathematical drying models for prediction drying kinetics behavior (Demir, *et al.*, 2007; Artnaseaw *et al.*, 2010).

Model name	Empirical drying equation	Equation no.
Page (1949)	$MR = \exp(-kt^n)$	(12)
Lewis (1985)	$MR = \exp(-kt)$	(13)
Henderson and Pabis (1961)	$MR = a\exp(-kt)$	(14)
Logarithmic (2001)	$MR = a\exp(-kt)+c$	(15)
Midilli *et al.* (2002)	$MR=a\exp[-k(t^n)]+bt$	(16)

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

$$MR=\left(\frac{8}{\pi^2}\right)\left[\exp\left(-\frac{\pi^2 D_{eff}t}{L^2}\right)+\frac{1}{9}\exp\left(-\frac{9\pi^2 D_{eff}t}{L^2}\right)+\frac{1}{25}\exp\left(-\frac{25\pi^2 D_{eff}t}{L^2}\right)\right]\times$$
$$4\left[\frac{1}{\lambda_1^2}\exp\left\{-\lambda_1^2\left(\frac{D_{eff}t}{r_0^2}\right)\right\}+\frac{1}{\lambda_2^2}\exp\left\{-\lambda_2^2\left(\frac{D_{eff}t}{r_0^2}\right)\right\}+\frac{1}{\lambda_3^2}\exp\left\{-\lambda_3^2\left(\frac{D_{eff}t}{r_0^2}\right)\right\}\right] \tag{17}$$

where D_{eff} is the effective diffusivity(m^2/s), t is drying time (s), L is the grain length (m) and r_o is the radius of the paddy kernel (m), and l means the zero order of Bessel function.

The average moisture content of experimental data was determined by means of data triplication and used for simulating with Equation 17. As the same evaluation as simulation of empirical drying model, the R^2 and RMSE values were used as the principal criteria for selecting the best drying model to describe the experimental data. The effective diffusivity of water can be correlated with temperature using the Arrhenius equation (Abalone *et al.*, 2006), as shown in Equation 18.

$$D_{eff}=D_o e^{\left(-E_a/R(T+273.15)\right)} \tag{18}$$

where D_0 is the Arrhenius factor (m^2/s), E_a is the activation energy (kJ/mol), R is the universal gas constant (8.314 kJ/mol-K), and T is the temperature (°C)

3. Results and Discussions

3.1 Equilibrium moisture content

From the experimental set-up, the experimental data of the EMC values for germinated SP 1 rice variety was determined for a surrounding temperature ranging of 40-60°C and correlated to the relative humidity (RH) ranging of 10-90%. These experimental values were statistically analyzed by non-linear regression method. The best fitted coefficients of the EMC equations were simulated and shown in Table 3. The results showed that the simulated results using Modified GAB model have a good relationship to the experimental results (R^2=0.9477; RMSE=0.0750). An example of the results of simulated EMC values among relative humidity of 0-100% compared to the exact values is shown in Figure 1. Thereafter, the modified GAB model was used to determine the relationship of temperature, RH, and EMC for the analysis of the thin layer drying equation and for the study of drying kinetics of germinated Suphanburi 1 paddy drying. These EMC values show the same trend as grain rice varieties which were examined by previous works (Chen, 1990; Soponronnarit, 1997; Tirawanichakul *et al.*, 2007; Bualuang *et al.*, 2011).

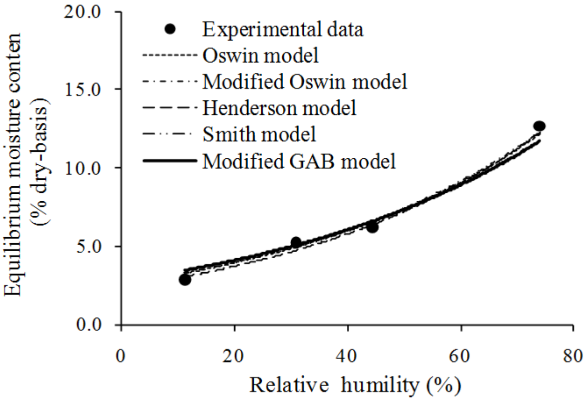

Figure 1. Equilibrium moisture content models of germinated Suphanburi 1 paddy among relative humidity of 10-90% for surrounding temperature of 60°C.

3.2 Apparent density

Apparent density of the germinated Suphanburi 1 (SP 1) rice variety was determined using Equation 3. Results from the determination of the apparent density of the rice showed that the apparent density is linearly related to its moisture content; it increased from 567.24 to 620.29 kg/m^3 when the moisture content increased from 13 to 47 % dry-basis. The result showed that the apparent density of germinated SP 1 paddy dependens on the moisture content corresponding to the results of other paddy cultivars and grain kernels (Soponronnarit, 1997; Bualuang *et al.*, 2007). The calculated results and the experimental results were plotted and illustrated in Figure 2. Additionally, the results stated that apparent density of germinated SP 1 paddy was linearly related to the moisture content. When the paddy kernel has high moisture content, the paddy kernel absorbs huge water content from the surrounding and thus the paddy kernel would be swelled. The apparent density would also be high. For evaluating

Table 3. Constant of equilibrium moisture content models for germinated Suphanburi 1 rice variety in range relative humidity of 10-90 %.

Model	Constants of model	R^2	RMSE
Oswin	A=0.0747 B=0.4296	0.9342	0.0841
Henderson	A=0.1641 B=1.7003	0.9083	0.9930
Smith	A=0.0262 B=0.0678	0.9375	0.0819
Modified GAB	A= 0.0405 B=0.8980C=10011.60	0.9477	0.0750
Modified Oswin	A= 0.0512 B=0.0001C=0.4304	0.9345	0.0839

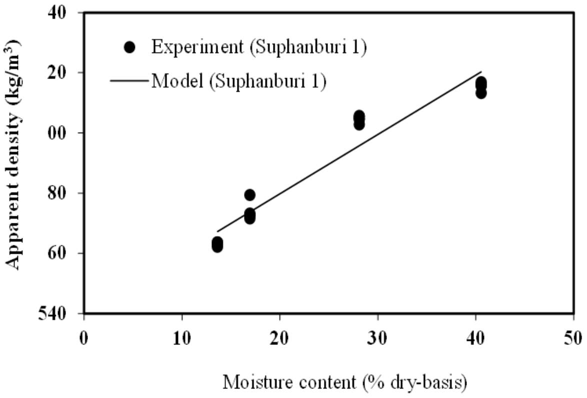

Figure 2. Relationship between apparent density and moisture content for germinated Suphanburi 1 paddy with moisture content of 13-47% dry-basis.

experimental data by linear regression analysis, the following equation of apparent density was expressed in form of a function of moisture content for germinated SP1 paddy variety as shown in Equation (19).

$$\rho = 1.970M + 540.384 \text{ with } R^2 = 0.931 \text{ RMSE} = 5.680 \quad (19)$$

where ρ is the apparent density of germinated grain kernel (kg/m^3), and M is the moisture content (%, dry-basis).

3.3 Percentage of void fraction

Void fraction of the germinated Suphanburi 1 paddy variety was determined using Equation 9. The void fraction means the space between paddy kernels. Results showed that the percentage of void fraction (% å) for the rice decreased with increasing moisture content. By linear regression analysis, the result showed that the percentage of void fraction linearly depends on the moisture content (Figure 3) and could be expressed by the following Equation 20.

$$\%\varepsilon = 55.307 - 0.144M \quad (10)$$
with $R^2 = 0.925$ RMSE $= 0.432$

where ε is percentage of void fraction of germinated grain (%), and M is the moisture content (%, dry-basis)

From Section 3.2 and 3.3, it is realized that the percentage of void fraction of germinated SP 1 paddy variety is inversely linear to the percentage of void fraction. These experiments are corresponded to the previous works in paddy and other biomaterial substances (Soponronnarit, 1997; Tirawanichakul *et al.*, 2007; Bualuang *et al.*, 2011).

3.4 Specific heat capacity

The experimental results were mathematically analyzed using linear regression method. The relationship between the specific heat and the moisture content for the germinated Suphanburi 1 rice was determined. Figure 4 shows the experimental values of the specific heat capacity (c_p) versus moisture content, and the line of best fit. The results showed that the specific heat capacity of the rice was directly proportional to the moisture content; it increased from 7.53 to 8.72 kJ/kg °C when moisture content increased from 13 to 47 % dry-basis. The specific heat capacity of the germinated SP 1 paddy was slightly higher than the parboiled paddy and normal paddy cultivars which were reported by some previous works (Soponronnarit, 1997; Tirawanichakul *et al.*, 2007; Bualuang *et al.*, 2011).

The following equation describing specific heat capacity of germinated SP 1 paddy was formulated in function of moisture content was expressed in Equation 21.

$$c_p = 0.037M + 6.987 \quad (21)$$
with $R^2 = 0.952$ RMSE $= 0.100$

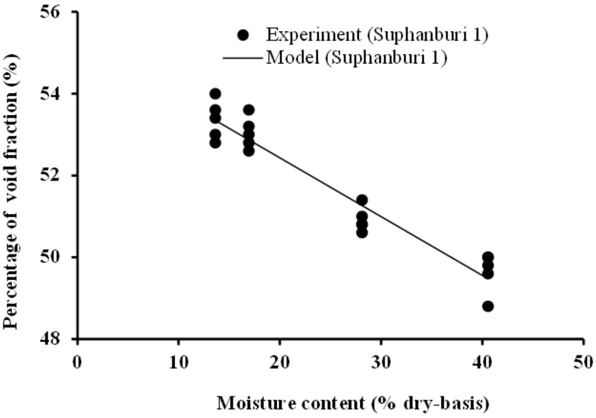

Figure 3. Relationship between void fraction and moisture content for germinated Suphanburi 1 paddy with moisture content of 13-47% dry-basis.

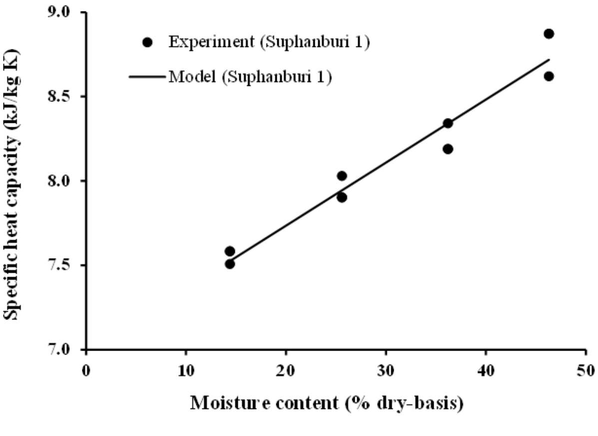

Figure 4. Relationship between specific heat capacity and moisture content for germinated Suphanburi 1 paddy with moisture content of 13-47% dry-basis.

where c_p is specific heat capacity of the germinated rice, and M is the moisture content (%, dry-basis).

All thermo-physical parameters in terms of EMC, apparent density, percentage of void fraction and specific heat capacity are useful for the prediction of the mechanism at large scale drying processes because these thermo-physical parameters will be changed during the drying period. However, the EMC value is not only used for the prediction of the moisture content of the samples when they were placed among the surrounding weather, but it also was used to predict the moisture ratio during the drying period.

3.5 Estimation of thin-layer drying model

The experiments were carried out at drying temperatures of 60 to 100°C and initial moisture content of 47 to 50% dry-basis and the electric infrared heating power was fixed at 1,000 W. The evolution of moisture transfer of germinated SP 1 paddy drying with two heat sources was continuously measured during drying time and the experimental data were curve-fitted following the empirical drying model. The drying rate of germinated SP 1 paddy variety which was determined by Equation 1 identified as falling drying rate period because at the beginning of drying period the moisture transfer was not constant. Table 4 showed the empirical drying models which were used for curve fittings experimental results. The result indicated that moisture ratio exponentially decreased with drying time and the drying rate depends on the drying temperature. Figures 5 and 6 illustrated the experimental and calculated results of germinated Sp 1 paddy drying with infrared radiation of 1,000 W and drying with hot air, respectively.

The results showed that for drying using IR radiation of 1,000 W, the calculated moisture ratio results using the empirical Midilli *et al.* (2002) Model had a good relation to the exact results (the R^2 and RMSE value of 0.9903 and 0.0180, respectively). For drying with HA convection, the Page Model provided the best curve fitting for their experimental results (the R^2 and the RMSE value of 0.9412 and 0.0419, respectively). Moreover, the germinated paddy drying

Table 4. Empirical constant and some statistical parameters obtained of five different thin-layer drying models by non-linear regression analysis.

Drying method	Constants of empirical drying model	R^2	RMSE
	Page model		
HA	k= 250.0684 exp(35948.5724/RT) n=1.3206	0.9412	0.0419
IR	k=3051.5879 exp(-34349.1732/RT) n=1.1245	0.9816	0.0247
	Lewis model		
HA	k= 67.2253 exp(-27937.5361/RT)	0.9143	0.1189
IR	k=1119.0781 exp(-30421.7231/RT)	0.9767	0.1614
	Henderson and Pabis model		
HA	k= 66.8728 exp(-27607.8421/RT) a=1.0396	0.9302	0.0456
IR	k=1175.1815 exp(-30428.1975/RT) a=1.0227	0.9800	0.0258
	Logarithmic model		
HA	k= 2.4684 exp (-27090.7261/RT) a=17.6332 b=-16.6139	0.9379	0.0430
IR	k= 941.9815 exp(-30529.9748/RT) a=1.2222 b=-0.2064	0.9806	0.0253
	Midilli *et al.* model		
HA	k= 0.0060 exp(-0.3836/RT) a=1.0213 b=0.0015 n=1.0287	0.7095	0.0930
IR	k= 397.4306 exp(-28765.5166/RT) a=0.9979 b=0.0065 n=1.3012	0.9903	0.0180

Note: HA – hot air drying; IR – infrared drying

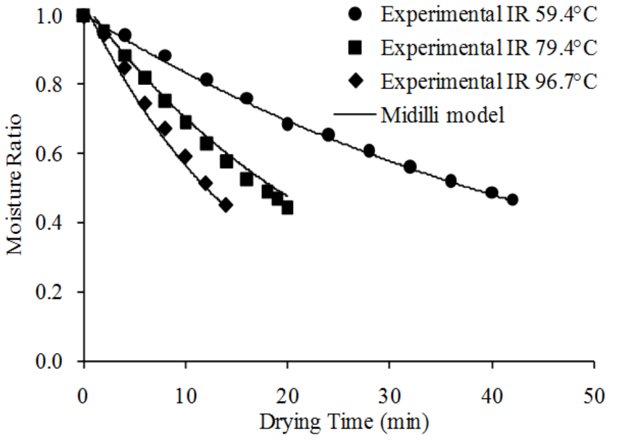

Figure 5. Comparison of the experimental data and predicted moisture ratio for germinated Suphanburi 1 paddy drying with infrared of 1,000 W at drying temperatures of 60-100°C.

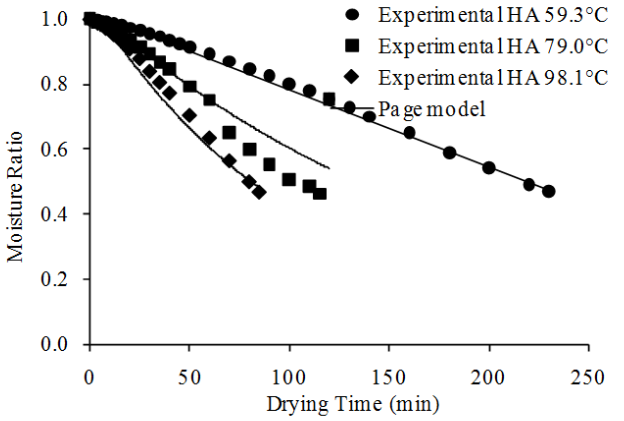

Figure 6. Comparison of the experimental values and predicted moisture ratio for germinated Suphanburi 1 paddy drying with hot air at temperatures of 60-100°C.

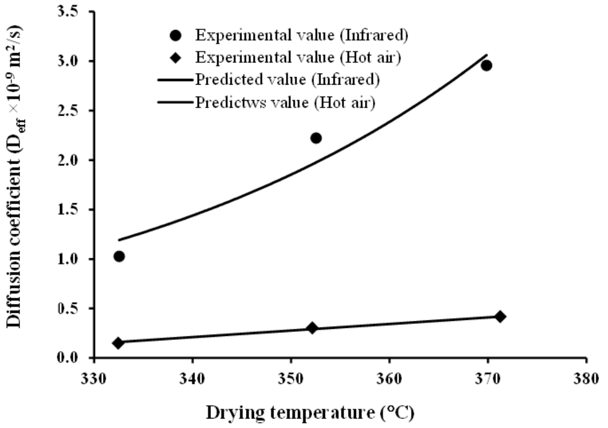

Figure 7. Comparison of the experimental data and predicted diffusion coefficient values for germinated Suphanburi 1 paddy dried with different heat sources (IR – infrared drying; HA – hot air drying).

rate with IR heat source was higher than that result obtained by HA heat source. This is because the energy in the form of electromagnetic wave (IR) can be transferred and thus the energy absorbed directly to the rice grain kernel by heat radiation with a low heat loss to the surrounding. So infrared radiation drying has relatively high heat transfer compared to the convection drying with hot air.

3.6 Effective diffusivity

From the thin-layer drying experiments, the effective diffusivity can be calculated employing a theoretical drying equation. The effective diffusivity values of the germinated Suphanburi 1 rice under infrared radiation 1,000 W drying and hot air drying are shown in Figure 7, with general indication that it depends on the drying temperature. The effective diffusivity of the germinated rice increased from 2.600×10^{-11} to 7.260×10^{-11} m^2/s under infrared radiation of 1,000 W, and more subtly from 2.515×10^{-12} to 8.019×10^{-12} m^2/s under hot air drying, when drying temperature was increased from 60°C to 100°C. At the same drying temperature, the effective diffusivity value when using infrared radiation was much higher than hot air. The equations for effective diffusivity derived from infrared radiation of 1000 W and hot air are respectively shown in Equation 22 and 23.

Infrared radiation (IR) :

$$D_{eff} = 1.324\times10^{-7}\exp(-23003.721/R(T+273.15)) \qquad (22)$$

R^2 = 0.921 RMSE = 0.551

Hot air (HA) :

$$D_{eff} = 3.418\times10^{-8}\exp(-25689.855/R(T+273.15)) \qquad (23)$$

R^2 = 0.927 RMSE = 0.062

From the evaluation of the effective diffusivity value of both drying heat sources, the activated energy (E_a) of germinated SP 1 paddy drying with IR was slightly lower than that obtained of HA. This implied that the energy for activation of moisture transfer of HA drying was relative high compared to the IR drying. This phenomenon was correlated to the fast drying rate of IR drying as shown in Figure 5, and corresponded to previous works (Afzal and Abe, 2000; Das *et al.*, 2009; Nuthong *et al.*, 2011).

4. Conclusions

The germinated paddy was the one staple food as the same as parboiled and normal brown rice because it has high nutrient content. In this work, the conclusion can be stated as following:

- The thermo-physical properties in terms of apparent density, specific heat capacity, and percentage of void fraction linearly depends on moisture content and these properties are essential for the design of the drying process and storage system, relatively related to grain moisture content.

- Simulation modeling of water sorption isotherms carried out by the commonly non-linear regression equations indicated that the Modified GAB model has the supremacy in prediction of equilibrium moisture content of germinated non-waxy paddy.
- Determination of effective diffusivity value using Fick's law of diffusion showed that the effective diffusivity of germinated paddy drying with infrared and hot air heat sources were highly dependent on drying time compared to the moisture content.
- The evolution of moisture transfer could be the exponential function of drying time and the drying rate was relatively dependent on the drying temperature. The simulated drying model of Midilli *et al.* (2002) had a good relation to experimental results of germinated SP 1 paddy drying with infrared radiation and the Page Model was also best fitting to the experimental results for drying with hot air convection.

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