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Thermo-Physical Properties And Mathematical Modeling Of Thin-Layer Drying Kinetics Of Medium And Long Grain Parboiled Rice

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This research was to investigate some thermo-physical properties and to determine a mathematical model for describing drying kinetics for medium and long grain parboiled rice varieties. The thermo-physical properties in terms of equilibrium moisture content (EMC), apparent density, void fraction, specific heat capacity at moisture content ranging from 30 to 58% dry-basis (d.b.) for both Leb Nok Pattani (LNP) and Suphanburi 1 (SP 1) rice varieties were determined by conventional standard techniques. The evaluated results showed that EMC values for both rice varieties predicted by the GAB's model yielded the best fitting with experimental data. To determine thermo-physical properties, the results stated that apparent density and specific heat capacity of parboiled LNP and SP1 rice varieties were linearly dependent on moisture content. In contrast, percentage of void fraction of medium grain LNP and long grain SP1 rice variety was inversely proportional to moisture content. For employing empirical thin-layer drying models, the Two terms model was the best fitting model to describe the experimental data for both rice varieties.

Keyword: Empirical drying model, Hydrothermal treatment, non-glutinous rice, Sorption isotherm, Thermo-physical properties

INTRODUCTION

Parboiling is defined as method of hydrothermal treatment given to paddy. Actually, parboiling process consists of soaking, heating (steaming) and drying. Parboiled rice is one of nutrition food due to migration of bran components into endosperm during hydrothermal treatment of soaking and heating (Bhattacharya & Rao, 1966; Bhattacharya, 2004). Parboiled rice quality is interesting point of view for Thailand because parboiling changes physicochemical, chemical and organoleptic properties of rice kernel (Saikura et al. 1994; Bhattacharya, 1996; Reddy & Chakraverty, 2004). It reduces stickiness and white belly whilst it increases head rice yield and yellowness value (Kimura, 1983; Kimura et al. 1991). This is because starch gelatinization brings about changes in the physicochemical properties of rice (Rao & Juliano, 1970; Kimura et al. 1991; Bhattacharya, 1985, Tirawanichakul et al. 2004). Some research works in Asean countries were interested in process of parboiling. This is not only value added of rice export but also the parboiling can reduce damage of fresh paddy during high humid weather. Fresh paddy harvested in rainy season has high moisture content, ranging from 25 to 35% dry-basis (d.b.). So storage of high moisture paddy causes the deterioration of rice kernel such as heat liberated by respiration (Nuri, 1980; Soponronnarit, 1997) Dry matter loss (Soponronnarit, 1997; Tirawanichakul et al. 2004), oxidation of carbohydrates and rancidity (Swinkels, 1985; Ramezanzadeh et al. 1999), intracellular fermentations, growth of bacteria or molds (Gras et al. 1985) and yellowing (Gras et al. 1989; Soponronnarit et al. 1998) etc. To avoid degradation of fresh paddy and make the value added of paddy, the fresh paddy with high moisture content can be parboiled. However, knowledge of thermo-physical properties of local medium grain and long grain rice varieties is necessary for design of suitable drying systems (Sahay & Singh, 1994; Soponronnarit, 1997) such as equilibrium moisture content, specific of void fraction, specific heat capacity and diffusion coefficient etc, especially on parboiled rice varieties. This is because identification the thermo-physical property is quality indicator and can characterize the quantitative values and processing conditions for a better quality of parboiled rice.

The objectives of this research were to evaluate thermo-physical properties in terms of apparent density, void fraction, specific heat capacity and equilibrium moisture content and to determine the suitable mathematical thin-layer drying model using empirical drying model for explanation evolution of moisture content of local medium grain and long grain parboiled rice cultivars.

MATERIALS AND METHOD

Sample Preparation

Fresh paddy of Leb Nok Pattani and Suphanburi 1 rice varieties were provided by the Rice Research Institute in Phatthalung Province, Thailand. The fresh paddy samples were washed in fresh water to remove immature grains and impurities and then were soaked at 70°C for 3 and 4 h for medium grain Leb Nok Pattani and long grain Suphanburi 1 rice variety, respectively. Thereafter, soaking water was drained out and the soaked paddy samples were steamed at 97 to 100°C for 30 min to obtain parboiled rice without white belly. Then the soaked paddy were placed on basket to reduce excess water content before drying.

Initial moisture content of Leb Nok Pattani and Suphanburi 1 soaked paddy was in ranges of 30-50% d.b and of 30-58% d.b., respectively.

Equilibrium moisture content (EMC) and mathematical modeling

The saturated salt solutions for achieving an equilibrium moisture content stage used in this experiments as follows KNO_3, NaCl, $Mg(NO_3)_2 \cdot 6H_2O$, $MgCl_2 \cdot 6H_2O$ and LiCl. These five saturated salt solutions provided relative humidity values of 10-90% among temperature ranging of 30-65°C (Henderson, 1952; Chung & Pfost, 1967; Thompson et al. 1968; Iglesias & Chirife, 1976; Cordeiro et al. 2006; Tirawanichakul et al. 2004; Tirawanichakul & Tirawanichakul, 2007) and then the samples and each saturated salt solution were put in airtight vials. To avoid disruption the results from direct contact of the solutions, the parboiled paddy sample was put in small stainless steel mesh basket which hold sample above the saturated salt solution. The sealed vials was placed in an incubator at surrounding temperatures of 30-65°C to obtain final dry matter weight. The moisture content was determined when the parboiled paddy sample weight remained unchanged after 2 consecutive weighings (±0.005 g). The time to achieve the equilibrium state between sample and saturated salt solution was approximately 15-20 days. The parboiled paddy samples were then weighed to determine the final moisture content (can be so-called equilibrium moisture content, M_{eq}) following the AOAC method (AOAC, 1995). The sample weight was evaluated by means of triplication.

Five EMC models were selected for the fitting of the experimental data. These models are Halsey, Oswin, BET, Henderson and GAB models as shown in Table 1. The experimental results were mathematical formulated by following these five EMC

Table 1 . Mathematical model for predict equilibrium moisture content of rice

Model	Equation	
Oswin model (1967)	$M_{eq} = A\left[\frac{(RH)}{(1-RH)}\right]^{B}$	(1)
Halsey model (1948)	$M_{eq} = \ln\left[\frac{\ln(RH)}{-\left(A/R(T+C)\right)}\right]^{1/B}$	(2)
BET model (1967)	$M_{eq} = \left[\frac{M_m C(RH)}{(1-RH)[1-C(RH)+(RH)]}\right]$	(3)
GAB model (1967)	$M_{eq} = \left[\frac{M_m Ck(RH)}{[1-k(RH)][1-k(RH)+Ck(RH)]}\right]$	(4)
Henderson model (1974)	$M_{eq} = \ln\left[\frac{\ln(1-RH)}{A(T+B)}\right]^{1/C}$	(5)

equations and all constants of the EMC equations were evaluated using the non-linear regression analysis. The highest value of coefficient of determination (R^2) and the least root mean square error (RMSE) value were used as the criteria for determining the best suitable fitting EMC model. The following equation of R^2 and RMSE value were written as:

$$R^2 = \frac{n\sum_{i=1}^{n} x_i y_i - \left(\sum_{i=1}^{n} x_i\right)\left(\sum_{i=1}^{n} y_i\right)}{\sqrt{n\left(\sum_{i=1}^{n} x_i^2\right) - \left(\sum_{i=1}^{n} x_i\right)^2}\sqrt{n\left(\sum_{i=1}^{n} y_i^2\right) - \left(\sum_{i=1}^{n} y_i\right)^2}} \quad (6)$$

where

n : is the number of pairs of data

x_i, y_i : are independent and dependent variable, respectively

$$RMSE = \frac{\left(\sum_{i=1}^{n}\left(data_{i,exp} - data_{i,model}\right)^2\right)^{1/2}}{N} \quad (7)$$

where $data_{i,exp}$ and $data_{i,model}$ are the data for the i^{th} sample with subscripts exp. and model mean experimental and predicted values in decimal (d.b.), respectively.

Specific heat capacity (c_p)

The specific heat capacity of the paddy was evaluated by a bomb calorimeter. Fifty grams of parboiled paddy was placed into a calorimeter. Fifty grams of hot distilled water (65°C) was added into the calorimeter and well-mixed thoroughly. Equilibrium temperature was evident then was recorded by K-typed thermocouple connecting to the data logger (Supcon Co. Ltd., China) with an accuracy of ±0.5°C. Five repetitions for each sample were carried out at the same conditions. Specific heat capacity of parboiled paddy was determined according to the following expression of eq. (8) (Tirawanichakul & Tirawanichakul, 1994; Soponronnarit, 1997).

$$c_p = \frac{\left[m_c c_c\left(T_{eq} - T_{ci}\right) + m_w c_w\left(T_{eq} - T_{wi}\right)\right]}{m_p\left(T_{eq} - T_{pi}\right)} \quad (8)$$

where c_p = specific heat capacity, kJ/kg°C

m_c, m_w, m_p = mass of the calorimeter, the water and the paddy, respectively, g

c_c, c_w = specific heat capacity of calorimeter and the water, respectively, kJ/kg°C,

t_e = equilibrium temperature °C

t_{ci}, t_{wi}, t_{pi} = initial temperature of calorimeter, the water and the paddy, respectively, °C.

Percentage of void fraction (ε)

The void fraction of both parboiled paddy varieties samples is normally defined as the fraction of the space in its bulk volume. In the present, rice samples were fulfilled into a 25 ml cylinder flask and vegetable oil was added into the cylinder until full in spacing between rice samples. The volume added of vegetable oil was recorded and the percentage of void fraction for parboiled rice kernel was evaluated as follows in eq. (9).

$$\varepsilon = \frac{V_{oil}}{V_{cylinder}} \times 100 \quad (9)$$

Where ε = percentage of void fraction, %

V_{oil} = volume of solution (vegetable oil), cm^3

$V_{cylinder}$ = volume of the cylinder, in cm^3

Apparent density (ρ)

The apparent density is the ratio of the mass sample of the parboiled paddy to its total volume. For determining an apparent density, the mass of samples were weighed by an electronic balance with an accuracy of ±0.01 g and volume was measured using a volumetric flask. The excess on the top of the cell was removed by sliding a string across it. The average value of apparent density each moisture contents were determined by mean of five replications. The following equation of apparent density was defined as eq. (10)

$$\rho = \frac{m}{V} \tag{10}$$

Where ρ = the apparent density of the parboiled grain, g/cm^3 or kg/m^3

m = mass of the parboiled grain, g or kg

V = the cylinder volume, cm^3.or m^3

Establishment of thin layer drying model

The parboiled paddy samples were dried in a thin layer drying to determine the effective diffusion coefficient. Data on moisture content versus drying time were used to find the suitable mathematical model to describe it and to find out the diffusion coefficient. The experiments were carried out at impingement air drying temperatures of 35 to 120°C with inlet air velocity fixed at 7.4±0.2 m/s. The inlet drying air temperature, the ambient air temperature and the grain temperature were measured by K-typed thermocouples connected to a data logger with an accuracy of ±1°C (Supcon Co. Ltd., China). The average initial moisture contents of the samples were in the ranges between 30 and 58% d.b. During the drying process, determining of moisture content for both paddy variety samples were carried out and evaluated at every 2 min interval following AOAC (AOAC, 1995).

Empirical Drying Model

For determination of drying kinetic, the empirical drying models were simulated and arbitrary constants in each model was determined by the non-linear regression.

Table 2. Mathematical models for predict drying behavior

Empirical model	Model equation	
Henderson and Pabis (1961)	MR=a(exp(-kt))	(11)
Newton (O'Callaghan *et al.* (1971)	MR=exp(-kt)	(12)
Two-terms [Henderson (1974)]	MR=a(exp(-kt))+b(exp(-gt))	(13)
Page Agrawal and Singh (1977)	MR=exp(kt^n)	(14)
Wang and Singh(1978)	MR=1+at+bt^2	(15)
Logarithmic [Yaldiz and Ertekin (2001)	MR=a(exp(-kt))+b	(16)

where MR : moisture ratio in decimal

a,b,g,n and k : arbitrary constants

t : time in min.

analysis. The six drying models were used for predicting the experimental results as illustrated in Table 2. The highest value of coefficient of determination (R^2) and the least root mean square error (RMSE) value were used as the criteria for determining the best suitable fitting empirical thin-layer drying model on experimental results.

Semi-theoretical Drying Model

The Fick's law of diffusion was used to describe the transport of water inside the sample surface in terms of diffusivity. The assumption in this work was stated that the medium grain and long grain parboiled rice kernel is of spherical, finite cylindrical, infinite slab and infinite cylindrical shape. Additionally, the moisture content of paddy is transferred by liquid diffusion while effect of shrinkage of parboiled rice kernel was negligible during drying period. By analytical method with an initial condition and the boundary conditions, the general solution of moisture ratio can be obtained as follows: (Crank, 1975)

For spherical shape,

$$MR = \frac{M - M_{eq}}{M_{in} - M_{eq}} = \frac{6}{\pi^2}\left[\exp\left(\frac{-\pi^2 Dt}{r_0^2}\right) + \left(\frac{1}{4}\right)\exp\left(\frac{-4\pi^2 Dt}{r_0^2}\right) + \left(\frac{1}{9}\right)\exp\left(\frac{-9\pi^2 Dt}{r_0^2}\right)\right] \quad 17$$

For finite cylindrical shape,

$$MR = \frac{M - M_{eq}}{M_{in} - M_{eq}} = \left\{\left(\frac{8}{\pi^2}\right)\left[\exp\left(-\frac{\pi^2 Dt}{l^2}\right) + \frac{1}{9}\exp\left(-\frac{9\pi^2 Dt}{l^2}\right) + \frac{1}{25}\exp\left(-\frac{25\pi^2 Dt}{l^2}\right)\right]\right\} \times \quad 18$$

$$\left\{(4)\left[\frac{1}{\lambda_1^2}\exp\left(-\frac{\lambda_1^2}{r^2}Dt\right) + \frac{1}{\lambda_2^2}\exp\left(-\frac{\lambda_2^2}{r^2}Dt\right) + \frac{1}{\lambda_3^2}\exp\left(-\frac{\lambda_3^2}{r^2}Dt\right)\right]\right\}$$

For infinite slab shape,

$$MR = \frac{M - M_{eq}}{M_{in} - M_{eq}} = \frac{8}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{(2n+1)^2}\exp\left[-\frac{\pi^2(2n+1)^2}{4L}Dt\right] \quad 19$$

For infinite cylindrical shape,

$$MR = \frac{M_t - M_{eq}}{M_{in} - M_{eq}} = 4\left[\frac{1}{\lambda_1^2}\exp\left(-\frac{\lambda_1^2}{r^2}Dt\right) + \frac{1}{\lambda_2^2}\exp\left(-\frac{\lambda_2^2}{r^2}Dt\right) + \frac{1}{\lambda_3^2}\exp\left(-\frac{\lambda_3^2}{r^2}Dt\right)\right] \quad 20$$

where :

D : the effective diffusion coefficient, m^2/s

l, L : dimension of parboiled rice sample,length, m

r_0, r : the radius of parboiled rice (0.00146 m and 0.00187 m for Leb Nok Pattani and Suphanburi 1, respectively)

t : drying time, s

λ_n : root of the Bessel function of the n^{th} kind of zero order (for this work, λ_1= 2.4048, λ_2= 5.5201, λ_3= 8.6537, λ_4= 11.7915, λ_5= 14.9309)

The effective diffusion coefficient (D) is conventionally described by the Arrhenius type equation as follows:

$$D = D_0 e^{\left(-\frac{E_a}{RT_{abs}}\right)} \quad (21)$$

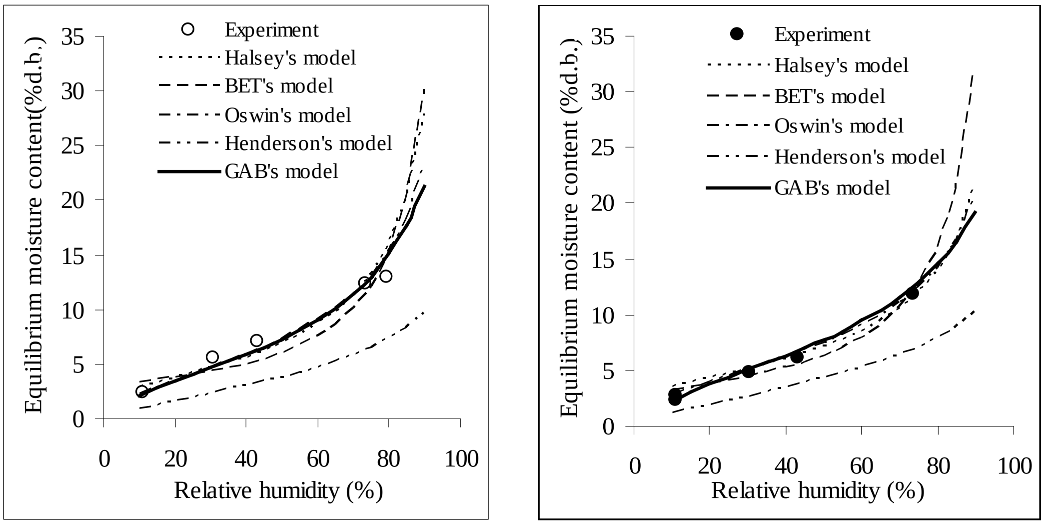
where :

- D_0 : Arrhenius factor of the heterogeneous solid, m^2/h or m^2/s
- E_a : the activated energy, kJ/mol-K
- R : universal gas constant, 8.314 kJ/kmol-K
- T_{abs} : absolute temperature, K

RESULT AND DISCUSSION

Modeling of the equilibrium moisture content (EMC)

Comparisons of equilibrium moisture content between predicted values of 5 EMC models and experimental values was shown in Fig.1(a) and (1(b) for Leb Nok Pattani and Suphanburi 1 rice variety, respectively.



(a) (b)

Fig. 1: Comparison between experimental data and predict data from equilibrium moisture content models for (a) medium grain Leb Nok Pattani parboiled paddy and (b) long grain Suphanburi 1 parboiled paddy

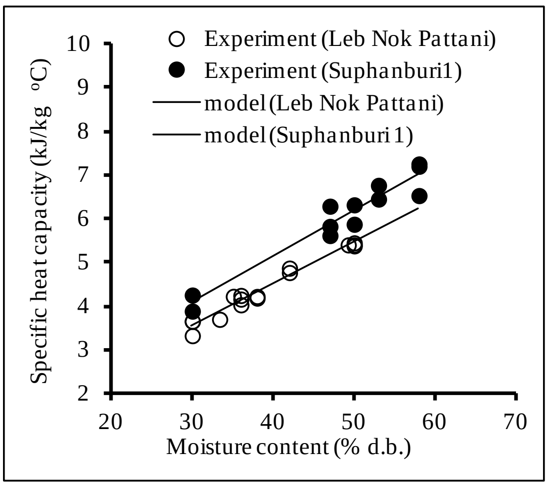


Fig. 2: Relationship of specific heat capacity at moisture content ranging of 16-50% d.b. and of 16-58% d.b. for medium grain Leb Nok Pattani parboiled paddy and long grain Suphanburi 1 parboiled paddy, respectively

According to the highest coefficient of determination (R^2) and the least root mean square error (RMSE), the results showed that the GAB's model was the best fitting model to the experimental values for the Leb Nok Pattani and the Suphanburi 1 paddy, respectively and the EMC were written as follows in eq. (22) and eq. (23).

For Leb Nok Pattani parboiled rice,

$$M_{eq} = \left[\frac{0.22576(RH)}{(1-0.683(RH))[1.0.683(RH)+4.51531(RH)]}\right] \quad (22)$$

at R^2 = 0.922 RMSE = 0.110

For Suphanburi 1parboiled rice,

$$M_{eq} = \left[\frac{0.294687(RH)}{(1-0.794(RH))[1.0.794(RH)+5.08081(RH)]}\right] \quad (23)$$

at R^2 = 0.957 RMSE = 0.098

Specific heat capacity (c_p)

By following the sub section mentioned in material and method section, the experiments of both parboiled rice varieties were carried on moisture content ranging of 16-58% dry-basis. The heat capacity was calculated by using eq. (8). The results showed that the specific heat capacity of medium grain (Leb Nok Pattani) and long grain (Suphanburi 1) parboiled paddy variety was a linear function of moisture content. The specific heat capacity ranging of 3.55-5.45 kJ/kg°C and 4.08-7.03 kJ/kg°C for Leb Nok Pattani and Suphanburi 1 parboiled rice was linearly dependent on moisture content of 30-58% d.b. as shown in following eqs. (24) and (25), respectively. The experimental results and simulated results were plotted in Fig.2. The figure showed that the specific heat capacity increased when the moisture content of parboiled rice kernel increased. This is because more water content inside rice kernel can more absorb heat. Additionally, the results stated that the long grain parboiled paddy (Suphanburi 1) has a slightly higher specific heat capacity than the medium grain parboiled paddy (Leb Nok Pattani). This may because weight of the long grain rice kernel is heavier than medium grain rice kernel.

For Leb Nok Pattani parboiled rice,

$$c_p = 0.095M+0.969 \quad (24)$$

R^2 = 0.969 RMSE = 0.121

For Suphanburi 1 parboiled rice,

$$c_p = 0.105M + 0.928 \quad (25)$$

R^2 = 0.931 RMSE = 0.262

Apparent density (ρ)

Results from the experiment showed that apparent density of both parboiled rice grain sizes was linearly related to moisture content. An apparent density increased with increasing moisture content as shown in Fig.3. For medium grain (Leb Nok Pattani) parboiled paddy, apparent density increased from 527.5 to 578.5 kg/m^3 when moisture content increased from 16 to 50% d.b. while apparent density of long grain (Suphanburi 1) parboiled paddy varied from 456.2 to 500.9 kg/m^3 correlated to moisture content ranges of 16-58% d.b. This may be because at the same weight of both parboiled paddy varieties, volume of long grain paddy variety was higher than that of short grain paddy variety corresponding to the previous work (Reddy & Chakraverty, 2004). The experimental results were then fitting curved by linear regression analysis and could be written as follows:

For Leb Nok Pattani parboiled rice,

$$\rho = 2.551M + 450.99 \quad (26)$$

R^2 = 0.945 RMSE = 0.546

For Suphanburi 1 parboiled rice,

$$\rho = 1.596M + 408.29 \quad (27)$$

R^2 = 0.963 RMSE = 1.545

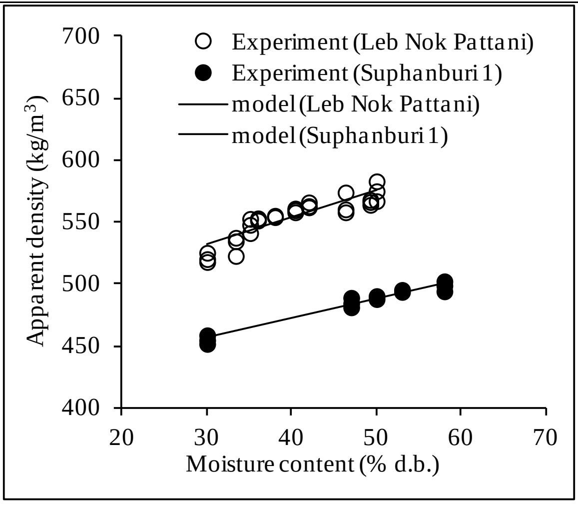


Fig. 3: Relationship of apparent density at moisture content ranging of 16-50% d.b. and of 16-58% d.b. for medium grain Leb Nok Pattani parboiled paddy and long grain Suphanburi 1 parboiled paddy, respectively

Percentage of void fraction (ε)

Evaluation of void fraction of both grain size parboiled paddy varieties among moisture content of 16-58% d.b. showed that the percentage of void fraction was inversely related to moisture content as illustrated in Fig. 4. The experimental values were formulated by linear regression analysis. The percentage of void fraction slightly decreased from 58.14 to 54.28% for medium grain Leb Nok Pattani parboiled paddy and from 64.54 to 55.70% for long grain Suphanburi 1 parboiled paddy. The simulated equations of both parboiled paddy varieties were presented in eqs. (28) and (29). Moreover, percentage of void fraction for medium grain Leb Nok Pattani paddy was less than long grain Suphanburi 1 parboiled paddy. This is because at the same moisture content the medium grain parboiled paddy kernels are more close together than long grain paddy kernels.

For Leb Nok Pattani parboiled rice,

$$\varepsilon = -0.193M + 63.940 \quad (28)$$

$R^2 = 0.954$ RMSE = 0.121

For Suphanburi 1 parboiled rice,

$$\varepsilon = -0.316M + 74.012 \quad (29)$$

$R^2 = 0.958$ RMSE = 0.262

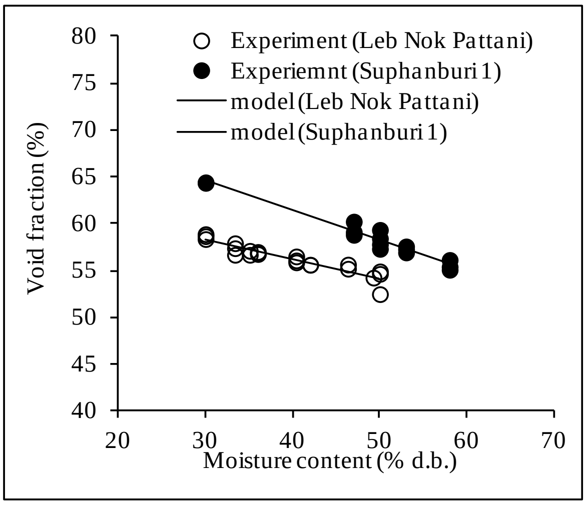


Fig. 4: Relationship between percentage of void fraction at moisture content ranging of 16-50% d.b. and of 16-58% d.b. for medium grain Leb Nok Pattani parboiled paddy and long grain Suphanburi 1 parboiled paddy, respectively

Mathematical modeling of thin layer drying

The experiments were carried on under the condition of drying temperature between 35 and 120°C. The results showed that drying rate of both grain sizes parboiled paddy varieties was highly related to drying temperature. In this work, the results showed that drying rate of parboiled paddy was only in falling drying rate as illustrated in Fig. 5 and 6. Fig.5 showed the evolution of moisture transfer of medium grain Leb Nok Pattani parboiled paddy during drying period with temperature of 120°C.

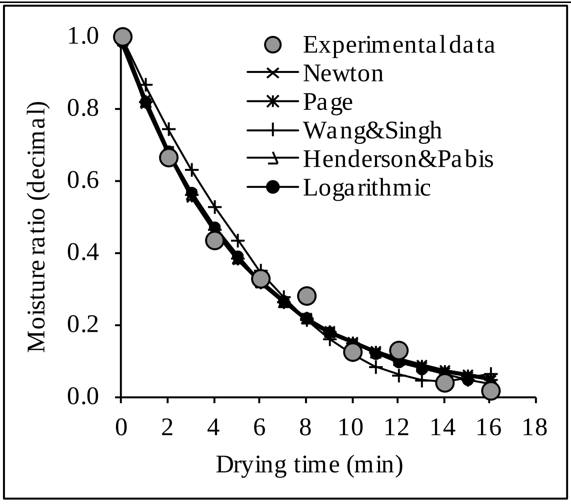
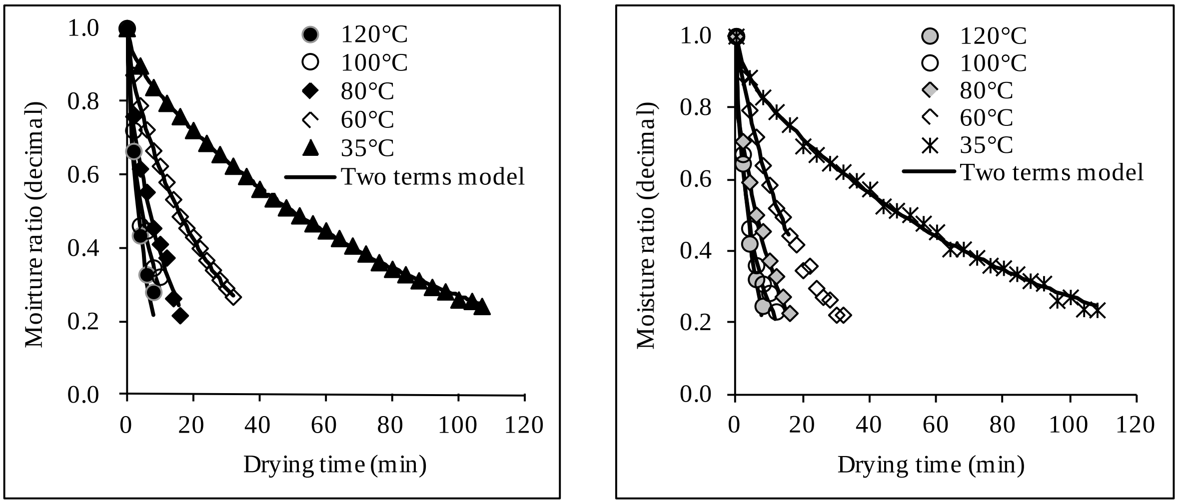


Fig. 5: Comparison between experimental data of Leb Nok Pattani parboiled paddy dying and empirical model at drying temperature of 120°C, air velocity of 7.4±0.2 m/s



(a) (b)

Fig. 6: Illustrative evolution of moisture transfer of experimental value and predicted value using Two terms model at drying temperature ranging of 35-120°C (a) medium grain Leb Nok Pattani parboiled paddy (b) long grain Suphanburi 1 parboiled paddy

According to the six empirical thin-layer drying models in Table 3, the experimental data was mathematical simulated using non-linear regression analysis. All arbitrary constants in each model were then evaluated. The predicted and experimental data were plotted in Fig.6 and the results showed that the Two terms model had a good relation to experimental results for both medium grain Leb Nok Pattani parboiled paddy and long grain Suphanburi 1 parboiled paddy cultivars (R^2>0.99). This phenomenon is corresponded to many works on paddy, other grain cereal kernels and sea food product (Henderson, 1974; Agrawal & Singh, 1977; Wang & Singh, 1978; Chen, 1990; Soponronnarit, 1997; Yaldiz & Ertekin, 2001; Jain & Pathare, 2007).

Actually, empirical thin-layer drying equation mostly predicts better than theoretical thin-layer drying models and semi-theoretical thin-layer drying models (Chen, 1990) and it is more convenient model compare to each others.

Evaluation of effective diffusion coefficient (D)

The diffusion coefficient of Leb Nok Pattani and Suphanburi 1 parboiled rice was in ranges of 6.33×10^{-10}-9.78×10^{-9} and 8.39×10^{-10}-1.35×10^{-8} m^2/s, respectively. The results showed that drying temperature affected relatively to effective diffusion coefficient and the relationship between effective diffusion coefficients and drying temperature were shown in figure 7. By determination of parboiled rice variety in forms of 4 different shapes, the results showed that both parboiled rice varieties in finite cylindrical shape had the best fitting to the experimental results. The following effective diffusivity coefficient equations for both parboiled rice varieties were written as function of temperature in eqs. (30) and (31).

For Leb Nok Pattani parboiled rice,

$$D = 3.000\times10^{-10}\exp(0.031T) \quad (30)$$

R^2=0.978 RMSE=1.411×10^{-1}

For Suphanburi 1 parboiled rice,

$$D = 4.000\times10^{-10}\exp(0.032T) \quad (31)$$

R^2=0.987 RMSE=1.567×10^{-1}

Where T : drying temperature, K

From the eq. (30) and eq. (31), they showed that an effective diffusion coefficient is in a form of Arrhenius equation (exponential model). This is because high different pressure in ambient air and drying material occur at high drying temperature, moisture content of material was easy diffuse throughout porous of material (Crank, 1975), it provide increase drying rate. Moreover, effective diffusion coefficient of long grain Suphanburi 1 rice variety was higher than of medium grain Leb Nok Pattani parboiled rice variety. This implies that Suphanburi 1 parboiled rice has more rapidly moisture content dehydration compared to medium grain Leb Nok Pattani parboiled rice. This incident is corresponded to the other thermo-physical properties which were evaluated in this paper and some previous researches (Soponronnarit, 1997; Tirawanicahkul et al. 2008). The figure 7 illustrated the example of effective diffusion coefficient of medium grain Leb Nok Pattani and long grain Suphanburi 1 parboiled rice which were in spherical shape and inlet impingement drying air speed of 7.4±0.2 m/s.

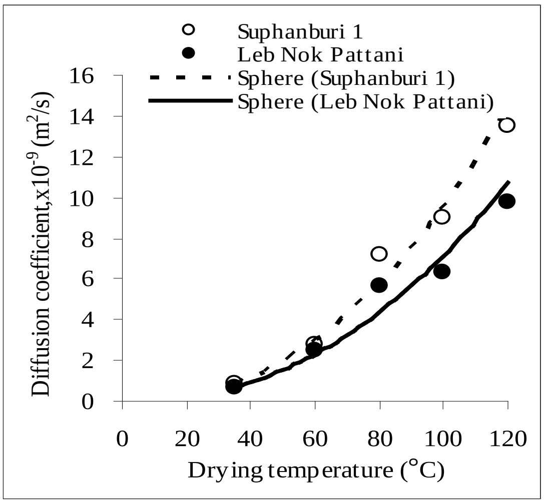


Fig. 7: Relationship between effective diffusion coefficient and drying temperature of medium grain Leb Nok Pattani parboiled rice and long grain Suphanburi 1 parboiled rice in form of spherical shape and inlet drying air velocity of 7.4±0.2 m/s

CONCLUSION

In conclusion of this study can be summarized that thermo-physical properties of medium and long grain parboiled rice varieties was dependent on moisture content of samples. The rate of moisture transfer during impingement drying for both parboiled rice exponentially related to drying temperature. Thermo-physical properties of parboiled paddy in terms of apparent density, equilibrium moisture content, void fraction, specific heat capacity were evaluated and the results concluded as follows:

1. GAB's model is the best model for predicting equilibrium moisture content of both rice varieties.
2. Apparent density, void fraction and specific heat capacity of both rice varieties are of linear functions in relation to the initial moisture content.
3. Specific heat capacity of the medium grain and long grain increased with increase of moisture content whilst the specific heat capacity value of the long grain rice variety was slightly higher than that of the medium grain rice variety at any given moisture content.
4. Percentage of void fraction of medium grain and long grain parboiled paddy decreased with increasing moisture content whilst percentage of void fraction for medium grain parboiled paddy was less than that of long grain parboiled paddy.
5. For studying drying kinetics employing the empirical thin layer model and diffusion theory, the results showed that predicted values of the Two terms model has a good relation to experimental data for medium grain and long grain parboiled paddy varieties. By solving the Fick's law of diffusion using analytical method, the results showed that the parboiled rice in forms of finite cylindrical shape has a good relation to experimental data.

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