

## DETERMINATION OF THE EFFECTIVE DIFFUSION COEFFICIENT AND THE HEAD RICE YIELD OF PARBOILED PADDY BY FLUIDIZED BED DRYING

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### ABSTRACT

In this study, the effective diffusion coefficient ( $D_{eff}$ ) of parboiled paddy in fluidized bed drying at high temperatures (110-170°C) and the head rice yield of milled parboiled rice were investigated. The results showed that the  $D_{eff}$  of parboiled paddy depended on drying temperature; the higher drying temperature provided higher  $D_{eff}$  value than the lower drying temperature. Higher drying temperature and lower moisture content after fluidized bed drying provided the significant decrease of the head rice yield of parboiled rice. It should not reduce moisture content of the parboiled paddy to lower moisture content of 27% (d.b.) in order to maintain the head rice. The appropriate moisture content after fluidized bed drying and tempering could improve the head rice yield.

**Keywords:** Fluidized bed drying; Thin-layer drying model; Diffusion coefficient; Head rice yield; Parboiled rice

### INTRODUCTION

Parboiled rice is mostly consumed in some Asian and African countries. The parboiled rice is produced by a hydrothermal process for improving milling yield [1]. Normally, parboiling process consists of three different operations, namely soaking, steaming and drying. After steaming, the moisture content of parboiled paddy was approximately 45-55% (d.b.), it should be dried to the safe moisture content before storage and milling.

Fluidized bed dryer has an effective means in drying and can apply to dry parboiled paddy. However, because of rapid drop of moisture content affect the quality of rice, especially head rice yield. Tempering step is practically used to reduce grain fissure [2]. It allows moisture diffusion from the interior to the external surface of the grain kernels to decrease the moisture- stresses inside the kernels and then reduces the rice fissuring. Consequently, the amount of broken rice decreases [3-4].

Therefore, the objective of this work is to investigate the drying characteristics of parboiled paddy by fluidized bed drying at high temperature and the effects of drying temperature, intermediate moisture content and tempering on head rice yield of parboiled rice.

### MATERIALS AND METHODS

#### Preparation of dried parboiled rice

The long grain paddy of Supanburi 1 variety was used in this study. The initial moisture content of the paddy was about 12-13% dry basis (d.b.). Paddy was soaked in water at temperature of 70°C for 5 hours. The soaked paddy was steamed by saturated steam at 120°C for 20 min. After that it was ventilated by ambient air until the grain temperature reached 29-30°C. The moisture content of the parboiled paddy was approximately 46-50% (d.b.). Two hundred g of the parboiled paddy was dried in a batch fluidized bed dryer at inlet drying air temperatures of 110-170°C, a superficial air velocity of 3.5 m/s and a bed height of 1 cm and the exhaust air was partially recycled with a fraction of 0.8.

For the drying characteristics determination, the samples was dried to different times of 0.5-6 min. After the predetermined drying time had been reached, the whole sample was taken out from the dryer to measure the moisture content. The grain temperature was measured within the drying chamber at 0.5 cm above the distributor. A new experiment was then conducted up to the next predetermined

drying time. These steps were repeated until the whole drying curve was obtained at each drying air temperature. In order to determine moisture content (MC), the MC of samples was determined by an electrical air oven at temperature of 103 °C for 72 hours, according to AACC method, 1995 [5].

For the determination of dried parboiled rice quality, a sample was dried to a moisture content of 27 and 22% (d.b.) and tempered in a closed jar for 30 min in order to reduce moisture stresses created during drying. In the last drying stage, the tempered sample was ventilated by hot-air at temperature of 45°C and a superficial air velocity of 1 m/s until the moisture content of the sample reached 14-16% (d.b.). After that the sample was kept in cold storage at 4-6°C for 2 weeks before quality analysis.

### Thin-layer drying model

In this study, the shape of the parboiled paddy kernel was considered as ellipsoid solid. The average dimensions of paddy kernel at 46% (d.b.) moisture content were 2.9×10.1×2.5 mm. The heat transfer from drying air to inside the rice kernel during drying process was considered to occur only by heat conduction and can be written as Eq. (1). Moisture transfer inside the rice kernel was explained by liquid diffusion, dried paddy is an isotropic solid and it was

explained by the Fick's second law [6] and can be written as Eq. (2).

Governing heat conduction equation and moisture diffusion for drying process can be written as

$$\rho_p c_p \frac{\partial T_p}{\partial t} = \frac{\partial}{\partial x} \left( k_p \frac{\partial T_p}{\partial x} \right) + \frac{\partial}{\partial y} \left( k_p \frac{\partial T_p}{\partial y} \right) + \frac{\partial}{\partial z} \left( k_p \frac{\partial T_p}{\partial z} \right) \quad (1)$$

$$\frac{\partial M_p}{\partial t} = \frac{\partial}{\partial x} \left( D_{eff} \frac{\partial M_p}{\partial x} \right) + \frac{\partial}{\partial y} \left( D_{eff} \frac{\partial M_p}{\partial y} \right) + \frac{\partial}{\partial z} \left( D_{eff} \frac{\partial M_p}{\partial z} \right) \quad (2)$$

where  $T_p$  is the grain temperature (K),  $c_p$  is the specific heat of paddy (J/kg.K),  $\rho_p$  is the density of paddy (kg/m<sup>3</sup>),  $k_p$  is the thermal conductivity of paddy (W/m.K),  $D_{eff}$  is the effective diffusion coefficient (m<sup>2</sup>/s),  $M_p$  is the moisture content of paddy (d.b.) and  $t$  is the drying time (s).

The corresponding initial and boundary conditions for Eqs. (1) and (2) are:

$$T(x, y, z, 0) = T_i, \quad M(x, y, z, 0) = M_i \quad \text{at } t = 0 \quad (3)$$

$$h_c (T_a - T_{ps}(t)) - \rho_p Q_{fg} \frac{V_p}{A_p} \frac{\partial M_{ps}}{\partial t} = k_p \left( \frac{\partial T_{ps}(t)}{\partial x} + \frac{\partial T_{ps}(t)}{\partial y} + \frac{\partial T_{ps}(t)}{\partial z} \right) \quad (4)$$

$$h_m (M_e - M_{ps}) = D_{eff} \left( \frac{\partial M_{ps}}{\partial x} + \frac{\partial M_{ps}}{\partial y} + \frac{\partial M_{ps}}{\partial z} \right) \quad (5)$$

where  $T_i$  is the initial grain temperature (K),  $M_i$  is the initial moisture content of paddy (d.b.),  $h_c$  is the convective heat transfer coefficient (W/m<sup>2</sup>.K),  $T_a$  is the drying air temperature (K),  $T_{ps}$  is the temperature of the grain surface at time  $t$  (K),  $A_p$  is the surface area of a single kernel (m<sup>2</sup>),  $V_p$  is the volume of a single kernel (m<sup>3</sup>),  $Q_{fg}$  is the latent heat of vaporization (W/m<sup>2</sup>),  $M_e$  is the equilibrium moisture content of paddy (d.b.),  $M_{ps}$  is the moisture content at the grain surface (d.b.) and  $h_m$  is the mass transfer coefficient (m/s).

The convective heat transfer coefficient and the latent heat of vaporization at grain surface can be determined by following relationship [7]:

$$Nu = 0.248 Re^{0.612} Pr^{1/3} \quad (6)$$

$$h_c = \frac{Nu k_a}{d_p} \quad (7)$$

$$Q_{fg} = 1000 \times (2500.8 - 2.3668 \bar{T}_{ps}) (1 + 2.496 e^{-21.733 \bar{M}_p}) \quad (8)$$

where  $Nu$  is the Nusselt number,  $Re$  is the Reynolds number,  $Pr$  is the Prandtl number,  $k_a$  is the thermal conductivity of drying air (W/m.K),  $d_p$  is equivalent diameter of the paddy (m),  $\bar{T}_{ps}$  is the average temperature of the grain surface at time  $t$  (K) and  $\bar{M}_p$  is the average moisture content of the grain at time (d.b.).

$$c_p = 1110 + 44.8 M_w \quad (9)$$

$$k_p = 0.0863 + 0.00134 M_w \quad (10)$$

$$\rho_p = \frac{551.6 + 311 M_d}{1 - (0.621 - 0.25 M_d)} \quad (11)$$

where  $M_w$  is the moisture content of paddy in wet basis unit (w.b.) and  $M_d$  is the moisture content of paddy in dry basis unit (d.b.).

The mass transfer coefficient was determined by Eq. (12) [10] and the equilibrium moisture content of paddy was determined by Eq. (13) [11]

where  $Sc$  is the Schmidt number,  $\rho_a$  is the density of air (kg/m<sup>3</sup>),  $c_a$  is the specific heat of air (J/kg.K),  $\alpha_a$  is the thermal diffusivity of air (m<sup>2</sup>/s),  $D_{wa}$  is diffusion coefficient of water vapor (m<sup>2</sup>/s),  $RH$  is the relative humidity of the drying air (decimal) and  $T_{abs}$  is the drying air temperature (K).

$$h_m = \frac{h_c}{\rho_a c_a \left(\frac{Sc}{Pr}\right)^{2/3}} = \frac{h_c}{\rho_a c_a \left(\frac{\alpha_a}{D_{wa}}\right)^{2/3}} \quad (12)$$

$$M_e = 0.01 \left[ \frac{\ln(1-RH)}{-3.146 \times 10^{-6} (T_{abs})} \right]^{-1/2.464} \quad (13)$$

The effective diffusion coefficient was described by an Arrhenius type equation, which is

$$D_{eff} = D_0 \exp\left(\frac{-E_a}{RT_p}\right) \quad (14)$$

where  $D_0$  is the Arrhenius factor (m<sup>2</sup>/s),  $E_a$  is the activation energy (kJ/kmol),  $R$  is the universal gas constant (kJ/kmol.K) and  $T_p$  is the grain temperature (K).

In this study,  $D_0$  and  $E_a$  were determined by a trial and error. The Comsol Multiphysics™ 3.3a simulation program (Comsol Inc, Palo Alto) based on the finite-element method and the number of mesh of 5,483 elements was used. The grain temperature values and moisture content values of parboiled paddy during drying at temperatures of 110-170 °C from prediction were used to compare as the experimental values for drying times of 0.5-6 min. The calculation will stop when the relative average error percentage was minimized and can be defined as below.

$$Error(\%) = \frac{100}{n} \sum_{i=1}^n \left| \frac{\bar{Y}_{prediction} - \bar{Y}_{experiment}}{\bar{Y}_{experiment}} \right| \quad (15)$$

where  $\bar{Y}_{prediction}$  and  $\bar{Y}_{experiment}$  are the values from prediction and experiment, respectively, and  $n$  is the number of observations. The values that was recorded from the experiments were the moisture content and grain temperature.

### Head rice yield evaluation

A 125 g of dried parboiled paddy was dehulled by a hulling machine (Ngeksenghuat,

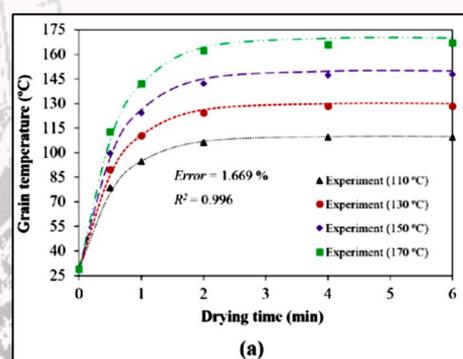
model P-1, Thailand) and milled to remove bran using a miller (Ngeksenghuat, model K-1, Thailand). The samples was graded using an indent cylindrical separator (Ngeksenghuat, model I-1, Thailand) to obtain a head rice. The head rice yield was defined as the mass of unbroken parboiled rice kernels (a length longer than 3/4 of the whole kernel length) divided by the mass of paddy before milling. All experiments were performed in duplicate and the average value was reported.

All experimental data were analyzed by the one-way analysis of variance (ANOVA) using SPSS software, version 14 and presented as mean values with standard deviations. Differences between mean values were established using Duncan's multiple range tests at a confidence level of 95%.

## RESULTS AND DISCUSSION

### Drying characteristics

Fig. 1 shows the changes of grain temperatures and moisture contents of the parboiled paddy during drying at temperatures of 110-170°C. When it was dried, the grain temperatures of parboiled paddy was rapidly increased in the two minute of drying and slightly increased after words. The end of drying, the grain temperature below the drying temperature was approximately 5-10 °C depending on the drying temperature. Simultaneously, the moisture content of parboiled paddy was rapidly decreased at the first two minute of drying. The decrease of moisture content at these drying times was not in a linear fashion, suggesting that the drying rate is in a falling rate period although the moisture content of parboiled paddy is very high. As expected, the moisture removal rate was higher at higher drying temperatures. The higher drying rate is due to the larger temperature gradients between paddy grain and drying temperature.



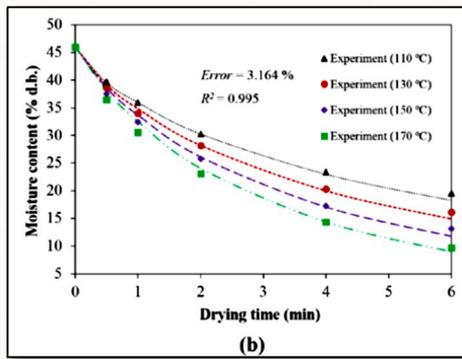


Fig. 1 Comparison of model predicted and experiment measured (a) grain temperatures and (b) moisture contents of the parboiled paddy during fluidized bed drying.

### Effective diffusion coefficient

The  $D_{eff}$  of parboiled paddy is shown in Fig. 2. The values of  $D_0$  and  $E_a$  obtained from this study were  $2.55 \times 10^{-7}$  m<sup>2</sup>/s and 20,580 J/kmol, respectively. The  $D_{eff}$  increased with increasing grain temperature. The value of  $D_{eff}$  varied between  $3.4 \times 10^{-10}$  -  $7.6 \times 10^{-10}$  m<sup>2</sup>/s at the drying temperatures of 110-170 °C.

The  $D_{eff}$  value of parboiled paddy found in the present work and the  $D_{eff}$  of paddy determined from the drying data obtained from Poomsa-ad et al. (2002) was compared as shown in Fig. 2. Poomsa-ad studied the drying of paddy at temperatures of 110-170 °C using fluidized bed dryer. Their experimental moisture and grain temperature data were used to determine the values of  $D_0$  and  $E_a$  using the model that was proposed in this study. As shown in Fig. 2, it was found that the values of  $D_0$  and  $E_a$  from Poomsa-ad data were  $5.35 \times 10^{-6}$  m<sup>2</sup>/s and 28,450 J/kmol, respectively. From the comparison showed that the  $D_{eff}$  value of non-parboiled paddy were higher than the  $D_{eff}$  value of parboiled paddy. This is because the starch gelatinization in the parboiled paddy kernel acts as moisture diffusion resistance in the drying process.

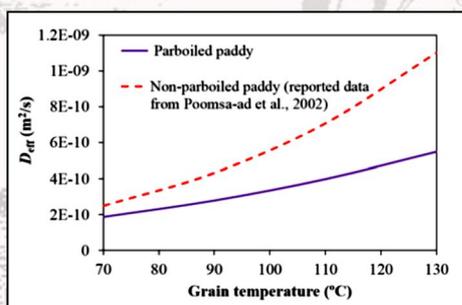


Fig. 2 Effective diffusion coefficients of parboiled paddy and non-parboiled paddy under thin-

layer fluidized bed drying, the modelling was coupled heat and mass transfer equations.

### Effects of moisture content and drying temperature on head rice yield

Fig. 3 shows the effects of moisture content after fluidized bed drying and drying temperature on the head rice yield of parboiled rice. The head rice yield of reference parboiled rice which was dried at 45°C was approximately 71.5%. After drying the head rice yield of parboiled paddy was decreased with decreasing moisture content. At the moisture content ranging between 27-44% (d.b.), the decrease of head rice yield did not depend on the drying temperature although the decrease of moisture content at higher drying temperature was more rapid. However, when the moisture content of parboiled paddy was dried below 27% (d.b.), the drying temperature became strong effect on the head rice yield. This is because the larger moisture gradient at higher drying temperature produces more tensile stress which was larger than the failure strength of parboiled rice. The head rice yield was rapidly decreased at higher drying temperature.

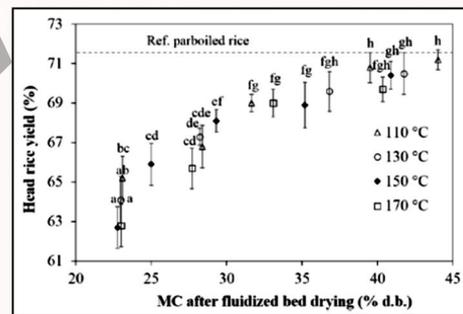


Fig. 3 Effects of drying temperatures and moisture content after fluidized bed drying on head rice yield of parboiled rice without tempering. Different letters above data point mean that the values are significantly different at  $p < 0.05$ .

### Effects of tempering, drying temperature and intermediate moisture content on head rice yield

To preserve the head rice, the dried paddy was tempered. The two moisture content dried paddy were selected of 22 and 27% (d.b.) as shown in Fig. 4. After tempering, the head rice yield quality became improved, the increase of head rice percentage was approximately 8-10% as compared to the parboiled rice without tempering for both intermediate moisture contents. This is because the moisture gradient and stresses that had been occurred during

drying has been relaxed during tempering, leading to lower rice fissuring. When compared to the head rice yield quality between both intermediate moisture contents, it can be seen that the dried parboiled paddy that was tempered at the moisture content of 27% (d.b.) was significantly higher than those that was tempered at the moisture content of 22% (d.b.). Also, the values of head rice yield at intermediate moisture content of 27% (d.b.) was almost close to that of reference parboiled rice, excepted for the sample which was dried at 170°C. As shown in Fig. 4, the head rice yield were insignificantly different amongst the tempered samples which was obtained from the drying temperatures of 110-150°C. From these results, it was recommended that the parboiled paddy should not be dried at temperature above 150°C and the dried parboiled paddy should be tempered at intermediate moisture content of 27% (d.b.), for parboiled paddy drying.

Fig.4 Effects of drying temperatures and different moisture content on head rice yield of parboiled rice which was dried at temperatures and tempered for 30 min. Different letters above bar graph mean that the values are significantly different at  $p < 0.05$ .

## CONCLUSIONS

The effective diffusion coefficient of parboiled paddy in fluidized bed drying and the head rice yield of parboiled rice was investigated in this work. It was found that the effective diffusion coefficient and grain temperature were correlated well by Arrhenius equation and the value of  $D_{\text{eff}}$  varied between  $3.4 \times 10^{-10}$ - $7.6 \times 10^{-10}$  m<sup>2</sup>/s at the drying temperatures of 110-170°C. Lower moisture content after fluidized bed drying of parboiled paddy caused the lower head rice yield for the sample without tempering. While, higher drying temperature insignificantly affected the head rice yield for the sample which was dried to 27-44% (d.b.) moisture contents, but it was significantly affected the head rice yield for the sample dried to the lower moisture contents of 27% (d.b.). Tempering could improve the head rice. When the parboiled paddy dried at temperatures to 27 and 22% (d.b.) moisture contents and tempered for 30 min, the percentage of head rice was increased approximately 8-10 % as compared to the samples without tempering.

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