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Experimental Investigation and Mathematical Modelling of Paddy Drying by Combined Infrared-Hot Air Fluidised Bed Technique

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ABSTRACT : *In this work, the drying system of paddy used the hot-air fluidised bed-drying technique combined with infrared heating (HAFBIR). Fives mathematical models (Page model, Two-term model, Wang & Singh model, Modified Saniso I model, and Modified Saniso II model) were developed for describing the thin-layer drying behaviour, which was conducted using a drying temperature of 110°C. The results found that the paddy rice was dried by the HAFBIR technique to reduce moisture content (MC) and achieve the required dryness approximately 50 s more than when using only the hot air fluidisation technique (HAFB). The head rice yield (HRY) of paddy dried by HAFBIR was circa 2% greater than the paddy dried by HAFB. When using HAFB, there was less collapse of the grain microstructure than using the HAFBIR technique. Also, out of the five models considered, the Wang & Singh model was determined to be the best fit for characterising the drying behaviour of both HAFB and HAFBIR dried paddy.*

KEYWORDS *Paddy drying, Mathematical modelling, Hot air fluidisation, Infrared.*

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I. INTRODUCTION

Rice is used as raw material for industrial parboiled rice production in Thailand. Rice has three levels of amylose: glutinous rice (includes 0-2% of amylose), low amylose rice (includes 10-20% of amylose), and high amylose rice (includes 25-33% of amylose). In industrial parboiled rice manufacturing, rice with low amyloses, such as Pathum Thani 1 and RD 15, and rice with high amylose, such as RD 49, are employed. In addition, San Pa Tong rice and RD 10 glutinous rice varieties and rice types with high amylose content, such as RD 19, Chainat 1, and Suphanburi 1, are also used. The selection of rice varieties for industrial parboiled rice production is essential in this regard. Rice varieties with a high yield per hectare and a low fracture after attrition percentage are recommended. According to research reports related to the production of parboiled rice abroad, it was found that glutinous rice is used, as are low amylose rice, medium amylose rice (includes 21-25% amylose), and high amylose rice as well. The proportion of rice consumption was mainly from rice with medium and high amylose content. In addition, both paddy and brown rice have been reported to be used as raw materials for the production of parboiled rice [1].

The procedure of making parboiled rice entails three crucial steps: soaking, steaming and drying the rice [1]. For steaming rice, saturated steam and steel boilers are used as the material. Rice husks are used as a source of steam. The drying technique that is used has a significant impact on the quality of a product. To improve the quality, traditional sun-drying techniques can be replaced by industrial drying methods such as spray dried [2, 3]. However, the parboiled rice sector in Thailand, on the other hand, makes the most use of fluidised bed dryers. Therefore, it consumes a significant amount of energy because of its impressive drying efficiency. Meanwhile, column dryers and mixed flow dryers (Louisiana State University, LSU) are efficient dryers for drying parboiled rice with consistent moisture decrease. However, the cost is exorbitant.

Drying materials with a hot air fluidised bed (HAFB) is an efficient approach. In the heated air utilised as a drying medium, the dried material floats freely. The drying air comes into contact with the material fast and evenly. The temperature inside the bed is uniform in all positions [4, 5]. The material is protected from local overheating even if the drying temperature is higher than the critical temperature. Thus, HAFB drying can use a higher drying air temperature than other drying methods, thus reducing drying time. HAFB drying is used for a variety of purposes, including paddy drying [6, 7], steamed brown rice drying [8], waxy rice drying [9], maise kernel drying [10] and soybean drying [11], etc. Therefore, it is necessary to improve the method for parboiled rice production by using HAFB and HAFBIR drying techniques. The drying kinetics and empirical mathematical modeling were analysed, and the quality (head rice yield and grain morphology) of the rice grains after drying was tested.

II. MATERIALS AND METHODS

Experimental procedure

The drying experiment of soaked paddy by HAFB and HAFBIR for parboiled rice production was performed at the Advanced Energy Laboratory, Faculty of Physics, Yala Rajabhat University, Thailand. The experiment used dry-soaked paddy (Si-Boo-Gan-Tang rice variety namely) from Waeng District, Narathiwat Province, Thailand, to produce parboiled rice at a bed height of 2.5±0.5 cm. Data including temperature, the weight of paddy, humidity, and hot air velocity were measured and recorded. The drying times were 0, 30, 60, 120, 180, 240, and 300 seconds. The moisture content (MC) at the time of drying, according to APLMF [12], was calculated as follows:

$$\mathrm{MC} = \frac{\mathrm{W} - \mathrm{d}}{\mathrm{d}} \times 100 \quad (1)$$

Where MC is the moisture content (% d.b.), W is the wet weight of paddy (g) and d is the dry weight of paddy (g).

Mathematical Modelling

The experimental drying data were analysed using the reduction of moisture ratio (MR) with drying time. The MR was calculated as follows [13-15]:

Page model: $\mathrm{MR} = \exp(-kt^n)$ (2)

Two-term model: $\mathrm{MR} = a.\exp(-k_0 t) + b.\exp(-k_1 t)$ (3)

Wang & Singh model: $\mathrm{MR} = 1 + at + bt^n$ (4)

Modified Saniso I model: $\mathrm{MR} = a.\exp(-kt^n) + k$ (5)

Modified Saniso II model: $\mathrm{MR} = \exp(-kt^n) + k$ (6)

Where MR is the moisture ratio (decimal), k is the drying constant, t is the drying time (s) and a, b and n are the arbitrary dimensionless constants.

HRY and morphology

The HRY of wet paddy dried by HAFB and HAFBIR was determined by dividing head rice weight (dehusked and polished rice) by initial rice weight (rice with husk). The results were calculated using the average of two determinations and expressed as a percentage as follows:

$$\mathrm{HRY} = \frac{W_f}{W_i} \times 100 \quad (7)$$

Where HRY is the head rice yield (%), W_i is the initial rice weight (g) and W_f is the head rice weight (g).

Meanwhile, the structural changes (microstructure morphology) of the soaked paddy dried by HAFB and HAFBIR were obtained using a scanning electron microscope (SEM) at an acceleration voltage of 5 kV. The images were captured at a magnification of ×2,000.

Data analysis

Data analysis was carried out to conclude from experiments on the mean moisture content. The moisture value of the soaked paddy during drying was calculated using the arithmetic mean ($\overline{X}$) and standard deviation (S.D.) as follows:

$$\overline{X} = \frac{\sum_{i=1}^{n} X_i}{N} \tag{8}$$

$$\text{S.D.} = \sqrt{\frac{\sum_{i=1}^{n} (X_i - \overline{X})^2}{N}} \tag{9}$$

By statistical analysis of the thin-layer mathematical modelling, the coefficient of determination (R^2) is the primary criterion for selecting the most suitable model to describe the drying curve equation. The root means square error analysis (RMSE) is also essential for the selection of a suitable model and standard error of the estimate (SEE) [13, 15, 16], as follows:

$$R^2 = 1 - \frac{\sum_{i=1}^{n} (MR_{exp.,i} - MR_{pre.,i})^2}{\sum_{i=1}^{n} (\overline{MR}_{exp.} - MR_{exp.,i})^2} \tag{10}$$

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{n} (MR_{exp.,i} - MR_{pre.,i})^2}{N}} \tag{11}$$

$$\text{SEE} = \frac{\sum_{i=1}^{n} (MR_{exp,i} - MR_{pre,i})^2}{d_f} \tag{12}$$

Where $\overline{X}$ is the arithmetic mean, S.D. is the standard deviation, RMSE is the root mean square error analysis, SEE is the standard error of the estimate, X is the experimental data, N is the number of trials, n is the number of experimental data, $MR_{exp,\,i}$ is the ith experimentally observed normalised moisture ratio, $MR_{pre,\,i}$ is the ith predicted value, df is the number of degrees of freedom of regression model, and i is an integer equal to 1, 2, 3, …

III. RESULTS AND DISCUSSION

Drying kinetics

HAFB and HAFBIR drying were performed by soaking the paddy in water at an ambient temperature for about two days (during soaking, the water was changed every 5±1 hours). After soaking, it was kept at room temperature for about 1 hour, after which the paddy was weighed at about 300 grams (corresponding with 2.5±0.5 cm bed depth). Subsequently, it was put in the drying chamber of the dryer system with a maximum drying temperature of approximately 110°C and a maximum infrared heater power of 500 W.

The results of the drying experiments were analysed. It was found that drying by the HAFBIR technique could reduce moisture content (MC) better than that drying with HAFB alone, as shown in Fig. 1. When rice grains are exposed to infrared radiation (IR), water molecules (moisture content) in the rice grains are vibrated, causing faster heat conduction in the rice grains. As a result, the inside of the rice grain is rapidly heated, causing the grain to be at a higher temperature than dried by HAFB alone. Heat accelerates the moisture content (accelerate the movement of moisture from inside to outside of the paddy grain) to change to vapor state and evaporate to the surface of the rice grain faster than that dried by HAFB alone. Therefore, HAFBIR drying can reduce moisture content faster than HAFB alone.

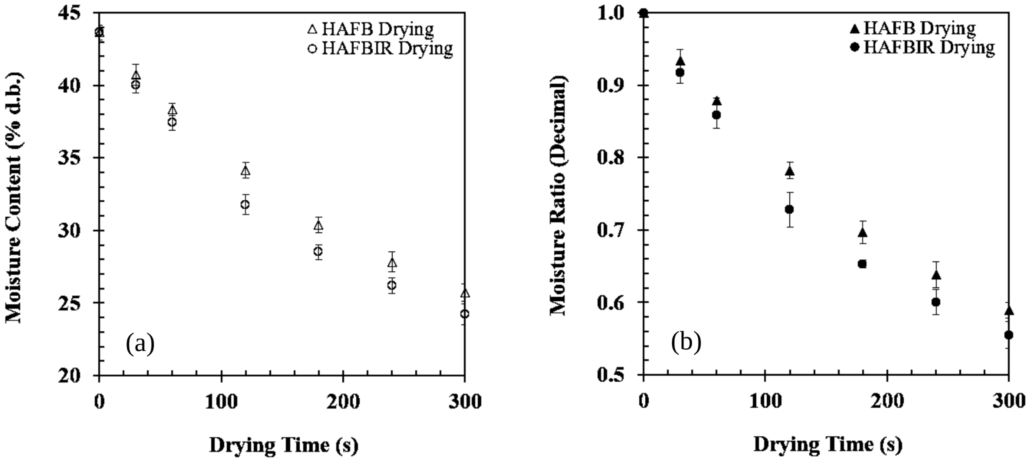

Fig. 1. Variation of (a) moisture content and (b) moisture ration with a drying time of soaked paddy dried by HAFB and HAFBIR at a drying temperature of 110°C (Each observation is a mean of two replicate experiments).

In addition, the difference in vapour pressure between the centre and the surface area of the paddy grain dried by HAFBIR was higher than that of the HAFB alone. This results in a faster water transfer from the inside of the paddy grain to the excess surface, thereby increasing the drying rate. The drying of paddy by HAFBIR until the final moisture content was approximately 26% d.b. Thus, it reduced the drying time by 50 s compared to drying by using HAFB at the same drying temperature.

Mathematical modeling

The MR versus drying time was fitted to the five thin layer drying models as shown in Table 1, and were analysed for their best fit based on the coefficient of determination (R^2), root mean square error analysis (RMSE), and standard error of the estimate (SEE). The results showed that the Wang & Singh model gave the highest R^2 of 0.9994 and 0.9989 for soaked paddy dried by HAFB and HAFBIR, respectively. Meanwhile, RMSE was the lowest at 0.004159 and 0.0000865, and the lowest of SEE at 0.0002715 and 0.007369 for soaked paddy dried by HAFB and HAFBIR, respectively.

Table 1. Curve fitting criteria for the various mathematical models of soaked paddy dried by HAFB and HAFBIR at a drying temperature of 110°C.

Model name	R^2	RMSE	SEE
HAFB Drying			
Page model	0.9990	0.005224	0.0001364
Two-term model	0.9969	0.012080	0.0004378
Wang & Singh model	0.9994	0.004159	0.0000865
Modified Saniso I model	0.9991	0.005709	0.0001304
Modified Saniso II model	0.9990	0.005222	0.0001364
HAFBIR Drying			
Page model	0.9949	0.0009042	0.013450
Two-term model	0.9891	0.0019130	0.025250
Wang & Singh model	0.9985	0.0002715	0.007369
Modified Saniso I model	0.3866	0.1079000	0.164200
Modified Saniso II model	0.9951	0.0008579	0.013100

The moisture contents were expressed as a dimensionless MR. The experimental MR and predicted MR by the Page model, Two-term model, Wang & Singh model, Modified Saniso I model, and Modified Saniso

II model were plotted as a function of drying time, as shown in Fig. 2 for HAFB and HAFBIR drying. To have a clear visual judgment, they were shown individually. It is evident that the Wang & Singh model effectively predicts the drying curves of soaked paddy as the data points of the predicted and observed moisture were identical for most of the drying time, as shown in Fig. 3.

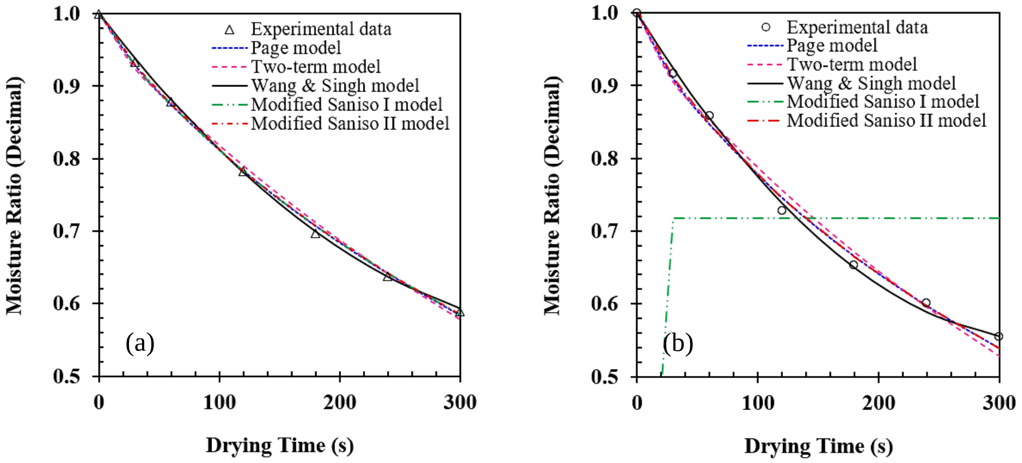

Fig. 2. Comparison of experimental and predicted MR values using Page model, Two-term model, Wang & Singh model, Modified Saniso I model, and Modified Saniso II model of soaked paddy dried by (a) HAFB and (b) HAFBIR at a drying temperature of 110°C

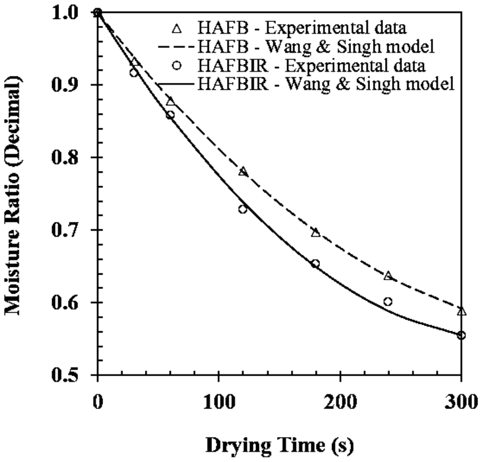

Fig. 3. Comparison of experimental and predicted MR values by the best fit model as Wang & Singh model of soaked paddy dried by HAFB and HAFBIR at a drying temperature of 110°C

HYR and SEM photographs

Head rice yield (HRY) of paddy was soaked and dried by HAFB and HAFBIR at a drying temperature of 110°C until the final moisture content is about 26% d.b. The results showed that HRY was increased with a drying time in the range of 58.1-66.7% and 59.3-68.2% for HAFB drying and HAFBIR, respectively. Thus, the HRY of paddy drying by HAFBIR was higher than that of HAFB drying alone. The soaked paddy dried by HAFBIR results in higher drying air temperatures than HAFB alone. As a result, the gelatinisation of rice starch is higher, and, therefore, the grain strength is more significant. [17] reported that the percentage of whole grains would decrease with a decrease in moisture content due to the accumulation of grain stress leading to cracks on the surface of the rice grains. An increase in the percentage of whole grains during drying may result from the gelatinisation of rice starches and thus the incorporation of rice starches, leading to the increased strength of the rice grains to withstand stress.

Meanwhile, the microstructure (morphology) of the rice grains dried by HAFBIR and HAFB technique were analysed by scanning electron microscope (SEM), as shown in Fig. 3, while the microstructure of the grain was dried by HAFBIR and HAFB alone. It was shown that the morphology of rice starches had a polygonal shape when dried by HAFB alone, as shown in Fig. 4(a), though the rice starch grains were still clearly visible. Conversely, the starch granule of soaked paddy dried by HAFBIR showed higher gelatinisation, resulting in molten rice grains. As a result, some of them lost the starch granules, prominently showing the collapse of the starches, as shown in Fig. 4(b). This is because HAFBIR can produce a higher grain temperature than that dried by HAFB alone.

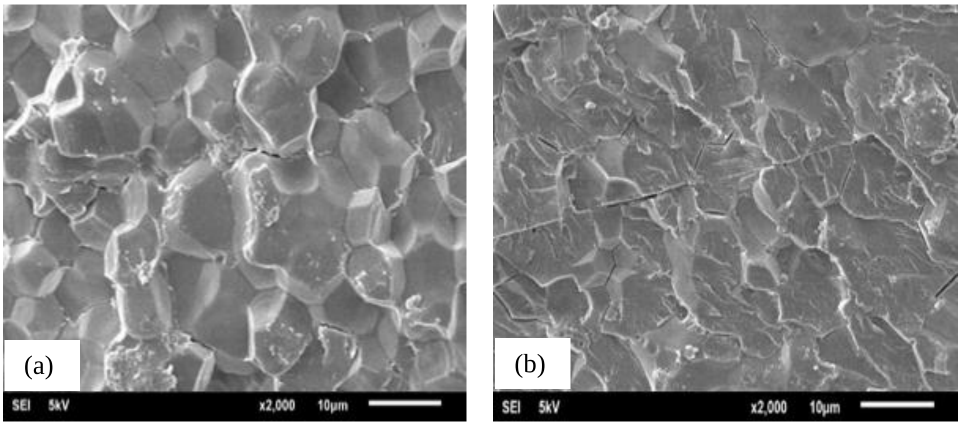

Fig. 4. SEM photographs of cross-sectional milled rice of soaked paddy dried by (a) HAFB drying and (b) HAFBIR drying

IV. CONCLUSION

The HAFBIR drying of wet paddy reduced the moisture content more than HAFB drying alone, and HAFBIR had a more significant percentage of HRY than HAFB drying. The HAFBIR drying collapsed the microstructure of rice grain more than HAFB drying, resulting in greater starch gelatinisation. While Wang & Singh's model is best equipped to predict MR from drying experiments, it also has the highest R^2 and the lowest RMSE and SEE for both HAFB and HAFBIR dried paddy.

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