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Drying Kinetics of Coconut Residue in Fluidized Bed

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Abstract – **This research aimed to investigate the effects of drying temperature (70, 80, 90 and 100°C) on dried coconut residue quality change in terms of oil content, whiteness value, and to determine suitable drying empirical model. To reduce moisture content of coconut residue from about 1.56 to 0.084 $g_{water}/g_{dry\ matter}$ by fluidized bed drying technique (constant velocity at 1.0 m/s), required drying time was in range of 4.3 - 8.0 min. Four of the well-known empirical models (*Newton*, *Henderson and Pabis*, *Page* and *Midilli et al.,*) were fitted to the fluidized bed drying of coconut residue. The *Page* model has shown an excellent fit to predict drying behavior of the coconut residue because this model gave the highest coefficient of determination (R^2), the least chi-square (χ^2) and the lowest root mean square error (*RMSE*). The higher the drying temperature, the shorter the drying time required. From the quality assessment, oil contents of dried coconut residue samples were close to each other and were higher than that of the fresh residue. Whiteness values of dried coconut residue were in the same range as that of the fresh residue. The dried coconut residue had oil content of 0.250±0.002 to 0.263±0.001 $g_{oil}/g_{dry\ matter}$ and whiteness value of 87.90±0.15 to 88.33±0.03 %.**

Keywords – **Coconut Residue, Fluidized Bed Drying, Empirical Model, Whiteness Values, Oil Content.**

I. Introduction

Coconut residue is the major by-product of the coconut milk extraction. Although the milk is extracted, the residue is still riches in nutrients and it can be utilized as a raw material for many kinds of products such as coconut flour, virgin coconut oil, and supplementary livestock feed (Trinidad *et al*., 2001). However, it poses a great problem to return to the coconut milk manufacturers due to its high moisture content and very short shelf life. Many studies have emphasized on drying of coconut residue to prolong its storage life before further processing (Niamnuy and Devahastin, 2005). Fluidized bed technology has been used in industrial dryers for drying wet particles and granular materials for many years owing to its many advantages, such as high rates of drying due to an excellent contact between the drying medium and the drying product, and high thermal efficiency (Mujumdar and Devahastin, 2003). Moreover, fluidized bed drying is a low cost drying system because its configuration is quite simple and easy to implement (Daud, 2008). Many researchers have performed using fluidized bed drying in many food and biomaterials. Nevertheless, information on fluidized bed drying of coconut products is inadequate. Niamnuy and Devahastin (2005) has studied drying kinetics of coconut dried using fluidized bed drying, but not coconut residue which is the major by-product from coconut milk extraction. Knowledge of the mathematical models of drying is required to design the drying process system. The thin-layer equations contributed to the heat and, mass transfer phenomena of agricultural products is required for designing new processes and improving existing commercial operations (Assawarachan et al., 2011). This study focused on the effects of air temperature on the drying characteristics, drying time, whiteness values and oil contents of dried coconut residue undergoing laboratory-scale of the fluidized bed drying. In addition choosing a proper mathematical model for thin-layer drying which can describe the drying kinetics of coconut residue was investigated.

II. Materials and Methods

A. Materials

Coconut residue obtained after the coconut milk extraction was provided by Ampol Food Processing Ltd., Thailand. Coconut residue then was washed and stored at 4±0.5°C in refrigerator for about one day for equilibration of moisture. To determine the initial moisture content, sixty 5 g of samples were dried by hot air drying at 105±2°C (Memmert, Model:500/108I) for 24 hr (AOAC, 2010). Five saturated salt solutions (LiCl, $MgCl_2$, $Mg(NO_3)_2$, NaCl and KNO_3) with their corresponding RH and approximately composition at 35˚C were applied to determine the equilibrium moisture content (M_e) of dried coconut residue (Bell and Labuza, 2000).

B. Drying Equipment and Drying Procedure

The sample of 150 g was dried in a laboratory fluidized bed dryer (Sherwood-scientific Model 50000101, UK). The experiments were operated at drying temperatures of 70, 80, 90 and 100°C, and at constant air velocity of 1.0 m/s. Coconut residue was dried from about 1.56 to 0.084 $g_{water}/g_{dry\ matter}$ moisture content.

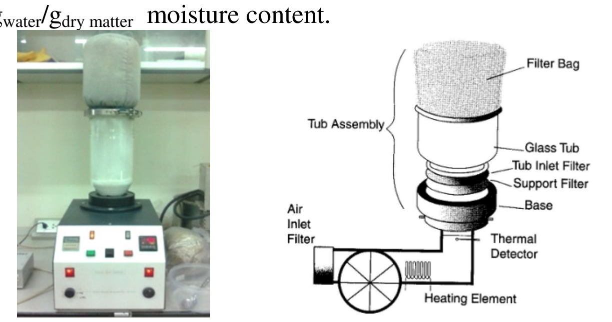

Fig.1. Schematic diagram of lab scale fluidized bed drying system

During drying, the samples were taken out periodically: at 30 sec interval for the first 0-3 min, and then at 1 min interval, weighted and recorded to determine the moisture content and fit drying models. Quality attributes, color and oil content, were analyzed only when coconut residue was dried to 0.084 $g_{water}/g_{dry\ matter}$

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C. Quality analysis

Whiteness - The color of dried coconut residue was measured CIELAB using Hunter spectrocolorimeter (ColorFlex Version 1.72, USA). Three parameters, namely L^* (lightness), a^* (redness/greenness), and b^* (yellowness/blueness) were measured. The whiteness (W) of samples was calculated as Eq 1.

$$W = 100 - \sqrt{(100 - L^*)^2 + a^{*2} + b^{*2}} \qquad (1)$$

Oil Contents- The 3 g of coconut residue and 50 ml of extract solution in extraction cups were extracted in the Soxtec system (Model: HT 104). The cups was then moved up to the boiling position for 15-20 min and moved down to the rinsing position to rinse for 30-45 min. In the final step, the extraction cups were dried in the hot air oven at 100°C for 30 min (Crowe and White, 2001). The percentage of oil content is calculated as Eq 2.

$$\%\ \text{Oil Contents}\ (g_{\text{oil}}/g_{\text{dry matter}}) = \frac{w_3 - w_2}{w_1} \qquad (2)$$

where w_1, w_2 and w_3 were weight of sample, weight of extraction cup (g) and final weight of extraction cup after extraction (g) respectively.

D. Mathematical modeling

Moisture content data obtained from the drying experiments was converted into the dimensionless moisture ratio (MR); they were calculated and using Eq 3:

$$MR = \frac{M_t - M_e}{M_i - M_e} \qquad (3)$$

where M_i, M_t, M_e and M_{t+dt} were moisture content (g water/g dry matter) at initial, specific time, equilibrium and $t+dt$, respectively; t was drying time (min). The correlation coefficient (R^2) was one of the primary criteria for selecting the best fitted model expressing the drying curves of the coconut residue. In addition to R^2, the chi-square (χ^2), and root mean square error (RMSE) were used to determine the consistency of the fit (Assawarachan et al., 2013; Jena and Das, 2007).These statistical values can be calculated as follows Eq 4-6:

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(MR_{\exp,i} - MR_{pred,i})^2} \qquad (4)$$

$$\chi^2 = \frac{\sum (MR_{\exp,i} - MR_{pred,i})^2}{N - n_p} \qquad (5)$$

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(MR_{pre,i} - MR_{\exp,i})^2} \qquad (6)$$

Where $MR_{\exp,\ i}$ was ith moisture content observed experimentally; $MR_{\text{pred},\ i}$ was ith predicted moisture content; N and n_p represented the number of observation and constants, respectively.

III. Results and Discussion

A. Drying characteristics

The initial moisture content (M_i) and equilibrium moisture content (M_e) of coconut residue were calculated 1.56 and 0.065 $g_{\text{water}}/g_{\text{dry matter}}$ as an average of the results obtained. The time required to dry coconut residue during fluidized bed drying from the initial moisture contents to the final moisture content of 0.084 $g_{\text{water}}/g_{\text{dry matter}}$ was achieved in 250, 280, 390 and 490 sec at 70, 80, 90 and 100°C of drying temperature, respectively. As expected, the moisture ratio (MR) was rapidly decreased from the beginning, and then showed down considerably as time went by Fig.1 showed the drying curves of coconut residue using fluidized bed dryer for different temperatures under a constant air velocity of 1.0 m/s. The moisture ratio of coconut residue reduced exponentially as the drying time increased. Drying air temperature had a significant effect on drying. At higher drying temperature, the drying time reduced due to the increase in water vapor pressure within the coconut residue, which increased the moisture removal.

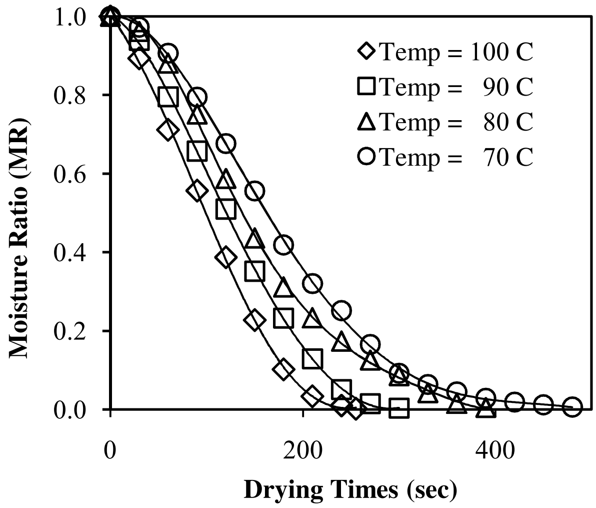

Fig.2. Effect of temperature on moisture ratio of coconut residue in the fluidized bed dryer

Drying curve of coconut residue during fluidized bed drying was found only in the falling rate period, and there was no constant rate drying period in these curves. It was observed that moisture ratio diminished dramatically in the early stage of drying, and ultimately changed a bit when close it was to desirable moisture content of around 0.084 $g_{\text{water}}/g_{\text{dry matter}}$. As expected, the higher drying temperature, the faster process to dry a sample to final moisture content of around 0.084 $g_{\text{water}}/g_{\text{dry matter}}$. Using the highest level of drying temperature of 100°C resulted in the highest drying rate of coconut residue.

B. Modeling Drying Kinetics

The non-linear regression analysis was used to determine the suitable mathematical modeling that best describes the fluidized bed drying of coconut residue. Four empirical models were fitted to the drying curve in order to select the best model for describing the drying curve. The average moisture contents data were observed in $g_{\text{water}}/g_{\text{dry matter}}$ during the fluidized bed drying at various different temperatures.

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Table 1: Regression coefficients thin layer drying models for coconut residue during fluidized bed drying

Drying Model	Drying Temperature	Empirical Drying Model Constants	R^2	$\chi^2 x 10^{-3}$	*RMSE*
Newton	70°C	*k*=0.0059	0.9741	8.24	0.0881
	80°C	*k*=0.0068	0.9794	7.01	0.0732
MR = exp (-*kt*)	90°C	*k*=0.0083	0.9760	8.03	0.0687
	100°C	*k*=0.0107	0.9791	6.03	0.0565
Henderson and Pabis	70°C	*k*=0.0066, *a*=1.1424	0.9777	6.07	0.0732
	80°C	*k*=0.0075, *a*=1.1233	0.9820	5.29	0.0611
*MR = a * exp* (-*kt*)	90°C	*k*=0.0091, *a*=1.0993	0.9781	7.15	0.0616
	100°C	*k*=0.0113, *a*=1.0671	0.9798	5.96	0.0530
Page	70°C	*k*=0.0056, *n*=1.7398	0.9993	0.18	0.0128
	80°C	*k*=0.0065, *n*=1.6284	0.9991	0.28	0.0140
MR = exp ($-kt^n$)	90°C	*k*=0.0079, *n*=1.6631	0.9978	0.74	0.0199
	100°C	*k*=0.0099, *n*=1.5287	0.9958	1.34	0.0251
Midilli *et al.*	70°C	*k*=0.0001, *n*=1.7898, *a*=0.9838, *b*=0.0000	0.9980	0.88	0.0260
	80°C	*k*=0.0004, *n*=1.5693, *a*=1.0177, *b*=0.0000	0.9979	0.81	0.0217
*MR = a*exp* ($-kt^n$) + *bt*	90°C	*k*=0.0001, *n*=1.8787, *a*=0.9159, *b*=-0.0001	0.9977	1.75	0.0269
	100°C	*k*=0.0000, *n*=2.1734, *a*=0.8193, *b*=0.0000	0.9895	5.59	0.0444

The best model describing the thin layer drying of agriculture product during fluidized bed drying was chosen as the one with the lowest χ^2, minimum values of *RMSE* and the highest R^2. The parameters of empirical mathematical model (*k, n, a* and *b*) and statistical analysis results applied to these models by taking into consideration with all air temperature are given in Table 2. In all cases of this study, the value of R^2 was greater than 0.99, indicating satisfactorily a good fitting. For all experiments, the R^2, χ^2, and RMSE values of the models altered in the extent of 0.9958-9993, $0.18x10^{-4}$ - $1.34x10^{-4}$, and 0.0128-0.0251 respectively. The results indicated that among these five models, the proposed *Page* model was the most appropriate model for prediction because it provided the highest R^2, while χ^2, and *RMSE* the were lowest. According to these results, the *Page* was the most suitable model in describing the fluidized bed drying behavior of coconut residue. Earlier studies by some researchers confirmed that the *Page* was also suitable for describing drying curve in many agricultural materials. Similar results for the order of reaction were found by other researchers as well.

C. Validation of the Empirical Mathematical Model

Based on the multiple regression analysis, the accepted model constants and coefficient were expressed in terms of the drying temperature (*T*). The relationship of constant parameters of empirical mathematical model (*k* and *n*) of the *Page* model in term drying temperature is demonstrated as follows:

$$k = 0.00017\,T - 0.0068 \quad (R^2 = 0.9712) \qquad (7)$$

$$n = -\,0.0059\,T + 2.148 \quad (R^2 = 0.7748) \qquad (8)$$

The suitability of the *Page* model for predicting the change of moisture content in coconut residue was validated with the defined condition. The constant parameters at air temperature 75, 85, and 95°C of *Page* model were calculated by equations (7) and (8). Fig. 3 presents the comparison between the actual and the predicted moisture content % (d.b.) in coconut residue by using the *Page* model from fluidized bed drying at 75, 85, and 95°C, respectively. The linear nature of the curve, with 45° slope from the origin, indicates that the predicted model was in a good fit with the actual moisture changes. The *Page* model of all drying temperatures gave the R^2 value higher than 0.95. Therefore, the result proved that the *Page* model was suitable for describing fluidized bed drying behavior of coconut residue.

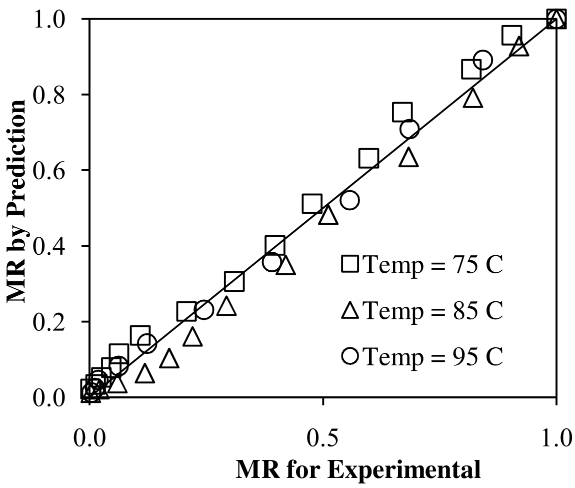

Fig.3. Experimentally determined and predicted moisture ratio of coconut residue during fluidized bed drying at air temperature 75, 85, and 95°C

D. Quality Change

The results show that whiteness values of dried sample at drying temperature of 70 and 100°C were not significantly lower than that of dried sample at drying temperature of 80 and 90°C and fresh sample. Moreover, it was no visible to the naked eye. This can be concluded that drying temperature was not influenced by whiteness values. This could be explained that the times which differed from each other up to only 490 sec which could not affect the whiteness values of dried coconut residue. Oil content of the dried sample using fluidized bed drying was up to 0.255±0.007, while all of results from fluidized bed drying were higher than 0.250 $g_{oil}/g_{dry\ solids}$. The highest oil content was 0.263±0.001 $g_{oil}/g_{dry\ solids}$ achieved from the dried sample by fluidized bed drying at 100°C and significantly different from others as indicated in Table 2. The results indicated that maximum drying temperature of 100°C made the highest oil content of dried sample, and it was the most suitable time for coconut residue using fluidized bed dryer. It is possible that using the higher drying temperature can obtain the higher oil content (Sopannttayanon et al., 2011). On the contrary, when whiteness values were considered, it was inversely proportional to drying temperature. Thus, the drying temperature should not be increased. Niamnuy and Devahastin (2005) explained that because the fluidized bed drying promotes intense particle movement, a higher air velocity causes the collision between the dryer and coconut pieces. Thus, it causes the squeezing action and consequently contributed to an excretion of the oil.

Table 2: The whiteness values and oil content of dried coconut residue under different fluidized bed drying conditions

Temperature (°C)	Whiteness (%)	Oil content ($g_{oil}/g_{dry\ solids}$)
Fresh	88.24±0.06^{a}	0.167±0.008^{a}
100	87.90±0.15^{b}	0.250±0.002^{b}
90	88.33±0.03^{b}	0.254±0.002^{b}
80	88.25±0.02^{b}	0.255±0.002^{b}
70	87.98±0.12^{c}	0.263±0.001^{c}

Note: Means within the same column followed by a different letter are significantly different at 5% level.

IV. Conclusion

The effects of air temperature on drying characteristics and the quality of coconut residue during fluidized bed drying process at different air temperature levels were investigated based on the whiteness value and %oil content. The best drying temperature level was found to be 100^{o}C, judging by the comparison of quality results obtained from the different air temperature levels. In this study, mathematical model for predicting the evolutions of the moisture content of coconut residue was successfully developed. The time required to dry coconut residue from initial moisture content of 1.56 to 0.084 $g_{water}/g_{dry\ matter}$ was 250, 280, 390 and 490 sec at 70, 80, 90 and 100^{o}C of drying temperature, respectively. According to these results, the *Page* model was the most suitable model for description of drying characteristic of coconut residue against time.

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