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Drying Kinetics of Steamed Glutinous Rice with a Free Convective Solar Dryer

Kongdej LIMPAIBOON[1] and Songchai WIRIYAUMPAIWONG[2]

[1]School of Agricultural Technology, Walailak University,
Nakhon Si Thammarat 80161, Thailand
[2]Faculty of Engineering, Mahasarakham University,
Kamriang, Kantarawichai, Maha Sarakham 44150, Thailand

(E-mail: lkongdej@hotmail.com)

ABSTRACT

The drying kinetics of steamed glutinous rice with a free convective solar dryer was studied and compared with open sun drying. The color of the dried product was also evaluated. The drying behavior of the steamed glutinous rice formed in the short cylindrical shape, known as Kao-Tan, from 100 % dry basis to a constant moisture level was investigated. Several drying models, namely Newton, Page, Henderson & Pabis and the Two term exponential were fitted to the data for both drying methods. The experimental results showed that solar dryer provided a higher air temperature and higher drying rate than open sun drying. The drying rate depended on the air temperature. The color comparison of the dried products between the 2 drying methods revealed that the solar dryer led to a significantly lighter, less red and less yellow product than that dried by open sun drying. From this study it can be concluded that a free convective solar dryer can be used to produce dried steamed glutinous rice well. Finally, the best drying model was Henderson & Pabis, whose model parameters was functioned with drying air temperature.

Keywords: Color, drying kinetics, steamed glutinous rice, solar dryer, models

INTRODUCTION

Sun drying is a useful application of solar energy with a low operating cost and can be used for many agricultural and food products. However, open sun drying has some disadvantages, i.e., contamination by dust and insects, cloudy weather and long drying periods. These promlems can be solved by using a solar dryer. Solar dryers comprise a collector, a drying chamber and sometimes a chimney. Solar dryers have been used to preserve fruits, vegetables, foods and other agricultural products in many countries [1-4]. Solar dryers are normally classified by air flow pattern such as natural or forced convective dryers [4,5]. To save energy in drying and initial investment cost, a type of natural convective dryer is often used namely a box-type solar dryer [6]. An advantage of the flat plate collector is that it still continues to operate when the weather is cloudy [7].

Kao-Tan, a crispy-food product, is made from steamed glutinous rice which is formed in a round shape, before undergoing drying and frying, respectively. In many regions of Thailand, Kao-Tan is a snack with different types of topping to add extra nutritional value. It is produced at home by traditional people with different recipes. Generally, open sun drying is used to reduce the moisture content of the glutinous rice after steaming. To eliminate water from steamed glutinous rice before frying and to store for longer periods, it is dried for 2 - 3 days. The number of days for drying depends on the weather. The low quality of the product is due to the insect, dust and other material contaminations. The advantages of the box type solar dryer are the simple and compact design, reduced contamination and no external energy requirement. The aims of this research are to dehydrate steamed glutinous rice in a box solar dryer and compare the product with that produced by open sun drying. In addition, the product color after drying and the best drying model were investigated.

MATERIALS AND METHODS

1. Solar Dryer

Figure 1 shows the box solar dryer with a free convective heat flow. This dryer consists of a drying chamber, a tray and a solar absorber combined into one unit. A simple chamber frame is fabricated of steel 1.20 m long, 0.60 m wide, 0.40 m high at the back and 0.15 m high at the front. Wooden sheets are set up on 4 sides of the dryer. A transparent glass sheet is placed on the top of the dryer. At the bottom side, an absorber plate is supported with foam and wooden sheets. The absorber plate is made of a galvanized metal sheet, painted black. A 0.25 m^2 perforated stainless steel tray is located in the middle of the dryer, where the steamed glutinous rice was placed. Nine holes each 2.5 cm in diameter were added to increase air flow. The inlet air holes were positioned at the front wooden sheet and the outlet air holes 5 cm from the top edge of the back wooden sheet of the solar dryer. The front side of the solar dryer was positioned facing east in the morning and turned to face west in the afternoon in order to maximize direct solar radiation. The air flows into dryer at the air inlet holes, passes through the product and brings the moisture into the air stream, which then flows out into the atmosphere through the air outlet holes.

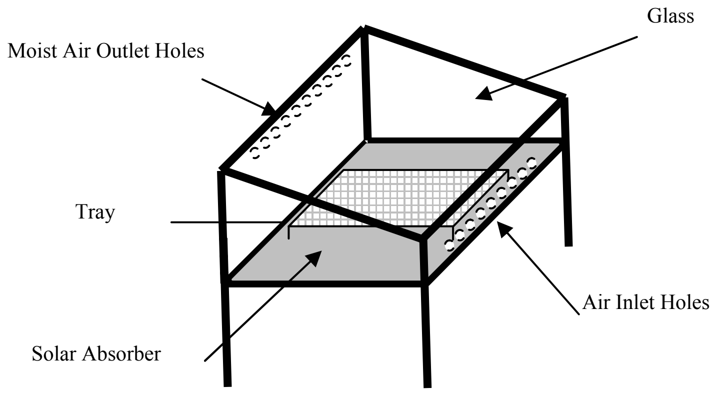

Figure 1 Features of the box solar dryer.

2. Experiments

Glutinous rice obtained from the local market was cooked in the earthenware steamer after being soaked in watermelon juice for several hours. The glutinous rice formed after steaming had a short, cylindrical shape with a diameter of 2.5 cm and a thickness of 1 cm. The solar dryer shown in **Figure 1** was used to study the drying kinetics of steamed glutinous rice and compared to open sun drying. The moisture content on a dry basis is the weight of water in the product per unit weight of dry solid in the product. It can be expressed by the following equations:

(a) Initial moisture content, M_i

$$M_i = \frac{W_i - W_d}{W_d} \tag{1}$$

where W_i is the initial weight of sample and W_d is the weight of the dry solid

(b) Final moisture content, M_f

$$M_f = \frac{W_f - W_d}{W_d} \tag{2}$$

where W_f is the final weight of sample

(c) Moisture content at any time, M_t

$$M_t = \left[\frac{(M_i + 1)W_t}{W_i} - 1 \right] \tag{3}$$

where W_t is the weight of sample at any time, *t*.

The initial moisture content of steamed glutinous rice was examined by oven drying at 103 °C for 72 h. The moisture at any time was calculated according to Eq. (3). The weight of the product after water removal was determined with an electronic balances. The drying air temperature inside the drying chamber and ambient temperature were measured with digital thermometers. Global solar irradiance was measured in the form of solar radiation flux density (in W/m^2) with a pyranometer. The experiments were executed under meteorological conditions at Walailak University in Nakhon Si Thammarat province during July - August 2008. For product color assessment, the lightness (L*), redness (a*) and yellowness (b*) were determined using a Hunter colorimeter. Then, the product color of each drying method was compared at similar final moisture content, 4 % dry basis, by DMRT statistical analysis.

3. Drying Kinetics Models

The moisture ratio (MR) and drying rate of steamed glutinous rice at any time during drying experiments are calculated by using the following equations.

$$MR = \frac{M_t - M_e}{M_i - M_e} \quad (4)$$

$$Drying \;\; rate = \frac{(M_{t-dt} - M_t)}{dt} \quad (5)$$

where M_{t-dt} and M_t are the moisture contents at $t-dt$ and t, respectively, and dt is the drying time period.

The drying kinetics data of the solar dryer and open sun drying were fitted to 4 published drying models, namely, Newton, Page, Henderson & Pabis and the Two term exponential as shown in **Table 1** [3]. The drying constant k is a function of ambient or drying air temperatures in form of an Arrhenius equation:

$$\text{Solar dryer:} \qquad k = b\exp(\Delta E / T_d) \quad (6)$$

$$\text{Solar drying:} \qquad k = b\exp(\Delta E / T_a) \quad (7)$$

where b is the constant parameter, ΔE is the activation energy, and T_d and T_a are the air temperature inside the solar dryer and ambient temperature, respectively.

Table 1 Mathematical models for describing drying kinetics.

Model name	Model expression
Newton	$MR = \exp(-k\,t)$
Page	$MR = \exp(-k\,t^n)$
Henderson & Pabis	$MR = a\exp(-kt)$
Two term exponential	$MR = a\exp(-kt) + (1-a)\exp(-kat)$

Note: *k*, *a* and *n* are drying constants.

Drying curves were fitted to 4 well-known drying models. Non-linear regression analysis was used to evaluate the parameters of each model. The goodness of fit was determined using the 2 statistical parameters, i.e. the coefficient of determination (R^2) and mean square error (MSE). These parameters can be described as follows:

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(MR_{exp,i} - MR_{pre,i})^2}{\sum_{i=1}^{n}(MR_{exp,i} - \overline{MR}_{exp,i})^2} \quad (8)$$

$$MSE = \frac{\sum_{i=1}^{n}(MR_{exp,i} - MR_{pre,i})^2}{n - z} \quad (9)$$

where $MR_{exp,i}$ is the experimental data, $MR_{pre,i}$ is the predicted data, $\overline{MR_{exp}}$ is the mean value of experimental data, *n* is the number of data and *z* is the number of constants in the model.

4. Efficiency of the Solar Dryer

This parameter is defined as the ratio of the energy required to evaporate the moisture to the energy supplied to the dryer absorber. The average solar drying efficiency is defined by the following equation.

$$\eta = \frac{m_w L_v}{I_T A_c \Delta t} \quad (10)$$

where m_w is the moisture evaporated, L_v is the latent heat of vaporization, I_T is the flux densities of solar radiation on the absorber surface, A_c is the area of absorber, and Δt represents the time during which the moisture is evaporated.

RESULTS AND DISCUSSION

1. Temperature and Solar Irradiance

The 300 grams of steamed glutinous rice at an initial moisture content of 100 % dry basis was dried for testing the solar dryer performance compared to open sun drying. Experiments were continuously carried out for 6 h. During drying time periods, the flux densities of solar radiation on the absorber surface (I_T) and temperatures of solar drying (T_d) and ambient air (T_a) were recorded at 30 min intervals and presented in **Figure 2**. The maximum drying air temperature in solar dryer was 75 °C. The average temperature difference of air inside the dryer and ambient air was 25.7 °C.

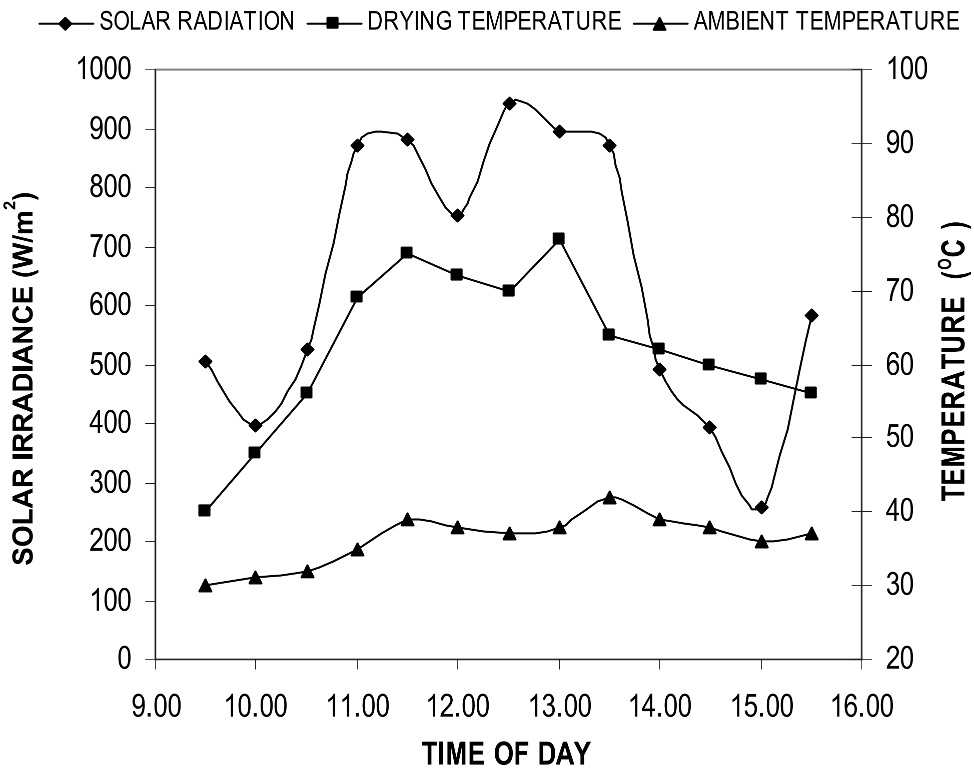

Figure 2 Flux density of solar radiation and temperature profiles during a typical day.

2. Drying Kinetics of Steamed Glutinous Rice

From the experimental data, the moisture contents (% db) of steamed glutinous rice for the solar dryer and open sun drying at any time are represented in **Figure 3**. It was clearly evident from these curves that the moisture content of steamed glutinous rice in the solar dryer decreased faster than that for the open sun drying. The moisture content of the steamed glutinous rice reached to 3.7 % dry basis in 6 h of drying in the solar dryer, whereas the final moisture content of the same product dried by open sun drying was only 28.4 % dry basis which this moisture content was not enough for safe storage. When it was dried by open sun drying, it generally took at least 2 sunshine days to bring it to the same moisture level. This can explained that the main factor influencing drying rate was the drying air temperature. Compared to open sun drying, solar dryer can generate higher air temperature and affected the significant increasing of evaporation rate of water and then led to lower final moisture content of drying samples. These results indicated that solar dryer was effective within 1 day.

Figure 4 shows the variation of the drying rate with moisture content of steamed glutinous rice for both drying methods, obtained by calculating from experimental data. The initial adjustment period of rise in temperature is ignored in the analysis of drying time. The drying rate for solar dryer comprises 2 distinct drying periods, that is, the constant-rate period and falling-rate period. In the constant-rate period, the steamed glutinous rice surface is wet and a continuous film of water exists on the surface having temperature approximately that of wet bulb temperature in the solar dryer. The energy received by the product is entirely used for vaporization of the surface water. For the falling-rate period, the surface is no longer wetted. The evaporation zone is now inside the product. The drying rate is controlled by diffusion of moisture from inside the product to the surface. Seen in **Figure 3** and **4**, the constant-rate period lasts for about 1 h and reduces the moisture content from 70 to 30 %, while the falling-rate period lasts about 4 h and reduces the moisture content from 30 to 3.7 %. For open sun drying, the entire drying rate is only in the falling-rate period from 80 to 28.4 % in 5 h due to low ambient temperature. The drying rate for the open sun drying decreases continuously with diminishing moisture content and is much lower as compared to that for solar dryer so the amount of moisture removed in open sun drying is relatively smaller.

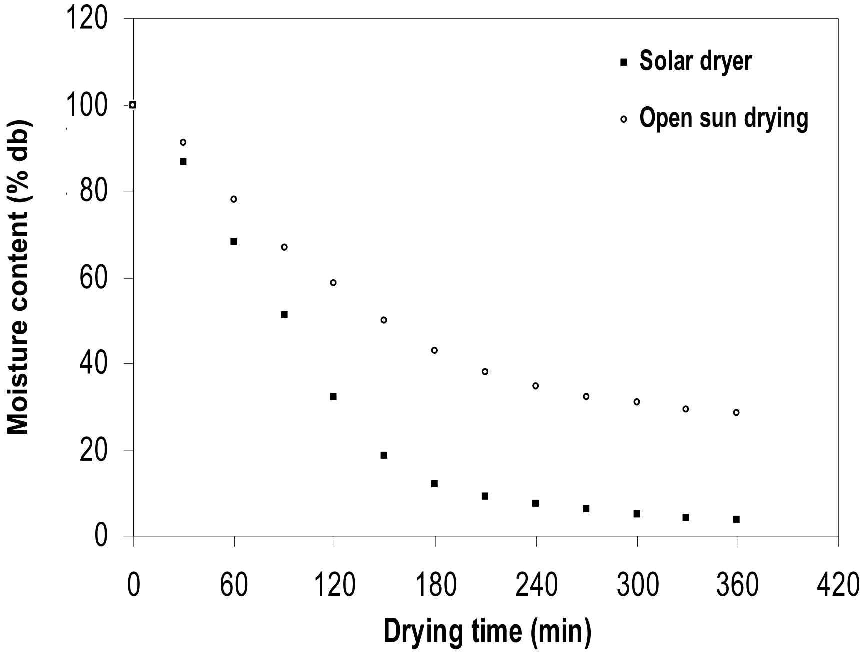

Figure 3 Drying kinetics of steamed glutinous rice by solar dryer and open sun drying.

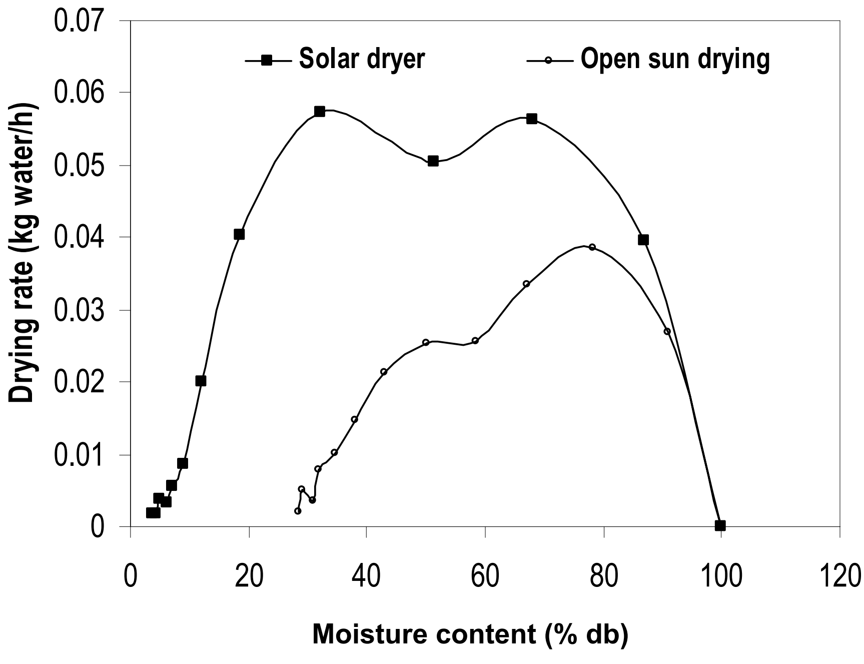

Figure 4 Drying rates of steamed glutinous rice by solar dryer and open sun drying.

3. Color of Steamed Glutinous Rice

The product colors after drying with a solar dryer and open sun drying are depicted in **Table 2**. They show the lightness, redness and yellowness of various samples. The solar dryer provided significantly different colors compared to the open sun drying products. The product color obtained from the solar dryer was lighter, less red and yellow than that obtained from open sun drying. This is due to a significant difference in drying temperature and drying time. In addition, visual color observations reveal the same trend as that determined from the colorimeter. However, the feature of each dried product obtained from both drying methods by visual assessment as shown in **Figure 5** remains a similar shape to the initial raw material. For the product colors after frying, it is found that they were independent of the drying methods (data not shown).

Table 2 Comparison between solar dryer and open sun drying of colors of dried steamed glutinous rice.

Color	Solar dryer	Open sun drying
L*	55.73 ± 1.00^{a}	42.88 ± 1.79^{b}
a*	11.10 ± 1.02^{b}	15.36 ± 0.97^{a}
b*	16.55 ± 1.21^{b}	20.75 ± 0.80^{a}

Notes: 1. Averages in the table are mean values ± standard deviations.

2. ^{a,b} within a row means significant difference by DMRT statistical analysis ($p < 0.05$).

(a) (b) (c)

Figure 5 Pictures of dried steamed glutinous rice (a) before drying, (b) after drying in a solar dryer and (c) after drying by open sun drying.

4. Modeling of the Drying Curve

The drying curves of the solar dryer and open sun drying were fitted to the different models as shown in **Table 1**. In order to determine the appropriate drying equation, the drying constants of the drying models were estimated from the experimental results using a nonlinear regression method. The best drying model was evaluated from (R^2) and MSE as depicted in **Table 3**. Newton and Henderson & Pabis models were compatible with the experimental data. However, the Page and Two term exponential models were not. The maximum R^2 and the minimum MSE were obtained in the case of the Henderson & Pabis model. The best fitted result of the model is shown in **Figure 6**.

Table 3 Modeling of moisture ratio versus drying time of steamed glutinous rice for the solar dryer and open sun drying.

Models names	**Drying method**	**Constants**			R^2	*MSE*
		a	**b**	**ΔE**		
Newton	Solar dryer	-	0.0279	–73.06	0.98	2.16E-05
	Open sun drying	-	0.0075	–21.63	0.99	9.62E-06
Page	Solar dryer	-	NA	NA	NA	NA
	Open sun drying	-	NA	NA	NA	NA
Henderson & Pabis	Solar dryer	1.0493	0.0242	–60.84	0.99	1.82E-05
	Open sun drying	0.9798	0.0092	–30.28	0.99	8.97E-06
Two Term exponent	Solar dryer	NA	NA	NA	NA	NA
	Open sun drying	NA	NA	NA	NA	NA

Note: Solar dryer: $k = b\exp(\Delta E / T_d)$ and open sun drying: $k = b\exp(\Delta E / T_a)$.

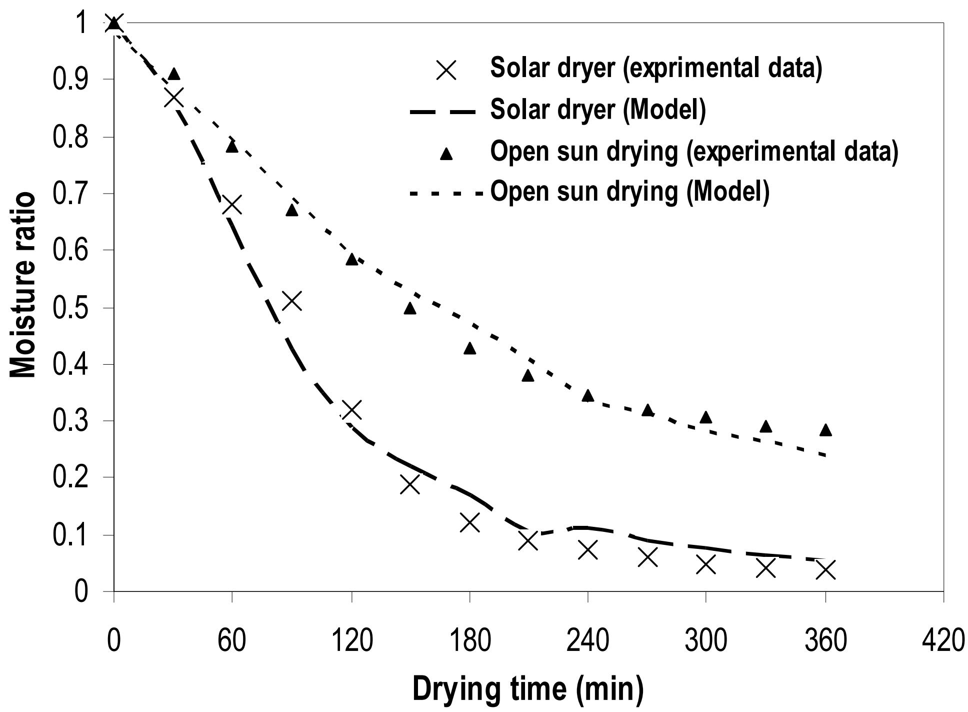

Figure 6 Comparison of the moisture ratio between experimental data and calculated values according to the Henderson & Pabis model.

5. Solar Drying Efficiency

The overall solar drying efficiency of the experiments during July-August 2008 is 8.16 %. This value is relatively low because of significant losses of sensitive and latent heat contained in the outlet gases. It is however relatively interesting since Singh [6] reports that solar drying efficiency reported in the literature is in a range of 4 - 23 %.

CONCLUSIONS

A box solar dryer with free convection was found to be a simple, compact system and more effective for steamed glutinous rice drying than open sun drying. It can dehydrate steamed glutinous rice in 6 h under meteorological conditions at Walailak University in Nakhon Si Thammarat province during June-August 2008. Therefore, the solar dryer is suitable for use in the production of dried steamed glutinous rice. However, the color of the product could be improved. The best drying model for describing the drying kinetics of steamed glutinous rice for 2 methods is the Henderson & Pabis model.

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บทคัดย่อ

คงเดช ลิ่มไพบูลย์[1] และ ทรงชัย วิริยะอำไพวงศ์[2]

จลนศาสตร์ของการอบแห้งข้าวเหนียวนึ่งโดยใช้เครื่องอบแห้งพลังงานแสงอาทิตย์

งานวิจัยนี้มีวัตถุประสงค์เพื่อศึกษาจลนศาสตร์ของการอบแห้งข้าวเหนียวนึ่งและสีของผลิตภัณฑ์โดยเครื่องอบแห้งพลังงานแสงอาทิตย์ที่มีการพาแบบอิสระโดยเปรียบเทียบผลที่ได้กับการตากแดดทั่วไป เครื่องอบแห้งพลังงานแสงอาทิตย์แบบตู้และวิธีการตากแดดทั่วไป จะถูกใช้ในการหาพฤติกรรมการอบแห้งของข้าวเหนียวนึ่งที่ทำเป็นชิ้นรูปทรงกระบอกสั้นๆ รู้จักในชื่อ ข้าวแต๋น จากค่าความชื้นมาตรฐานแห้งเริ่มต้น 100 เปอร์เซ็นต์ อบจนถึงสมดุลความชื้น สำหรับโมเดลจลนศาสตร์ของการอบแห้งที่นำมาใช้ คือ โมเดลของ Newton โมเดลของ Page โมเดลของ Henderson & Pabis และโมเดล Two term exponential จากผลการทดลองแสดงให้เห็นว่า เครื่องอบแห้งพลังงานแสงอาทิตย์จะมีอุณหภูมิของลมร้อนและอัตราการอบแห้งสูงกว่าการตากแดดทั่วไป โดยที่อัตราการอบแห้งขึ้นกับอุณหภูมิของลมร้อนด้วย และสีของผลิตภัณฑ์ที่ได้จากการอบแห้งทั้งสองแบบ พบว่า ผลิตภัณฑ์ที่ได้จากการอบแห้งในเครื่องอบแห้งพลังงานแสงอาทิตย์ จะมีความสว่างมากกว่า โดยมีสีแดงและสีเหลืองน้อยกว่าผลิตภัณฑ์ที่ได้จากการตากแดดทั่วไป จากการศึกษาครั้งนี้ กล่าวสรุปผลได้ว่า เครื่องอบแห้งพลังงานแสงอาทิตย์แบบตู้ที่มีการพาแบบอิสระสามารถนำมาใช้อบแห้งข้าวเหนียวนึ่งได้ดี สุดท้ายนี้ โมเดลที่เหมาะสมที่สุดในการอธิบายจลนศาสตร์ของการอบแห้ง คือ โมเดลของ Henderson & Pabis ซึ่งค่าพารามิเตอร์ต่างๆของโมเดลนี้ถูกหาในรูปฟังก์ชันของค่าอุณหภูมิอบแห้งด้วย

[1]สำนักวิชาเทคโนโลยีการเกษตร มหาวิทยาลัยวลัยลักษณ์ อำเภอท่าศาลา จังหวัดนครศรีธรรมราช 80161

[2]คณะวิศวกรรมศาสตร์ มหาวิทยาลัยมหาสารคาม อำเภอกันทรวิชัย จังหวัดมหาสารคาม 44150