Drying Characteristics of Paddy Dried by Thermosyphon Heat Pipe Heat Exchanger

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Abstract

It is well known that drying is an important method for avoiding the chemical and biochemical deterioration of paddy. Moisture reduction using solar drying is the most widely used method due to a low cost operation. However, it takes a very long time for the operation and an unstable climate may cause operation limitations, resulting in the quality of paddy. The Thermosyphon heat pipe heat exchanger is an alternative device applied in this study. The objective was to study the paddy drying characteristics of San-Pah-Tong 1 with average initial moisture content of 34.57% (wet basis) dried to final moisture content of 14% (wet basis). The layer thickness of paddy was 5, 10 and 15 centimeters. The results showed that the paddy drying using a Thermosyphon heat exchanger provided 3.5 times higher in average drying rate than that using open sun. The layer thickness of 5 centimeters was found to be shorter in drying time than 10 and 15 centimeters. Different mathematical models namely Henderson and Pabis, Midilli et al., Page, Modified Page and Logarithmic models were used for the modeling of the drying kinetics. The best mathematical model was determined using R^2 coefficient, root mean square error (RMSE) and chi-square ($\chi 2$) as criteria. It was found that the Logarithmic equation was the best model for describing the drying behavior in all cases. The effective moisture diffusivity evaluated by using Fick's diffusion equation was in the rage of 2.11×10^{-8} - 1.37×10^{-7} m^2/s.

Keywords: Drying characteristics, Thermosyphon, Heat exchanger, Paddy dried

Introduction

Paddy is one of the most important crops in the world. According to FAO report[1], global paddy production yielded about 745 million tons in 2013. After harvesting, paddy still contains high moisture content (19-26% wet basis)[2,3] that can cause nutritional losses and microbial growth during storage. To prevent quality deterioration paddy needs to be dried until a safe moisture level of 14% wet basis or below[4].The reduction of moisture is one of the oldest techniques for food preservation. Mechanical and thermal methods are two basic methods to remove moisture in a solid material[5]. Open sun drying is usually used to reduce moisture content of paddy. This method is a low-cost method and easy to operate. Nevertheless, it depends on the weather condition and consumes time. To overcome these problems hot air drying using Thermosyphon heat pipe heat exchanger was proposed in this study. This method has been reported to require shorter drying time than open sun drying leading to better product quality[6]. Thermosyphon heat pipe is one type of heat exchange device that has no external power requirements. Heat exchangers with heat pipe units possess many advantages such as high heat recovery effectiveness, high compactness, no moving parts, light weight, relative economy, pressure tightness, complete separation of hot and cold fluids, and high reliability[7]. Heat pipe heat exchanger has been extensively applied in many industries[8]. Thermosyphon heat pipes operate by using the heat transfer principle of latent heat of working fluid contained inside heat pipe.

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High temperature heat source caused working fluid evaporation. The working fluid of gas was condensed to be condensate by transferring heat to an area that had low temperature, which was the heat sink. Typical operation of heat pipe could be explained as follows. After the heat pipe receives heat at the evaporator section, the inside saturated working fluid evaporates to become vapor gas and then flows upward to the condenser section where there is a lower temperature. The working fluid transfers heat out by condensation and then the condensate returns downward to the evaporator section by gravity force to receive heat at evaporator section again. The operation, thus, acted as a cycle. Because of the high latent heat inside working the fluid, the heat pipe could be operated by transferring heat from one end to the other end although it had small difference temperature of the evaporator section and condenser section. He heat transfer capability of Thermosyphon heat pipe depends on several factors such as aspect ratio, length of heat pipe, type or material used to make the heat pipe, conditions of heat pipe setting, type of working fluid, temperature of heat source and temperature of heat sink[9].

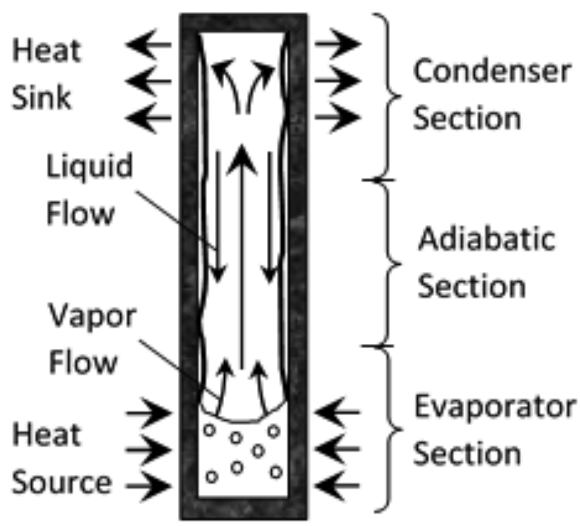

Figure 1 A schematic of the Thermosyphon[10]

In order to the clarify knowledge from the past study of Thermosyphon heat pipe heat exchanger and to apply on paddy drying, it is important to study the applied Thermosyphon heat pipe heat exchanger to reduce moisture content of paddy. This work therefore was aimed at investigating drying characteristics of paddy San-Pah-Tong 1 dried by hot air drying using Thermosyphon heat pipe heat exchanger drying method.

Experimental

1. Sample preparation

After harvesting of paddy (San-Pah-Tong 1) with average initial moisture content of 34.57%, (wet basis) paddy were then packed in zip bag and kept at 4°C until the time of experiment.

2. Heat Exchanger drying method

In this research a Thermosyphon heat pipe heat exchanger with seamless steel was designed and constructed as shown in (Figure 2) Thermosyphon heat pipe heat exchanger consists of a number of individual Thermosyphons or gravity-assisted wick less heat pipes. Distilled water was used as the working fluid with a filling ratio of 50% of the evaporator section length and consisted of 53 tubes that were 1.1 m long, had a 25 mm inside diameter and a 30 mm outside diameter. The tubes were arranged in 7 rows. The evaporator and condenser sections of the Thermosyphon heat exchanger had a length of 500 mm and its central adiabatic section had a length of 100 mm. The parameters are shown in (Table 1).

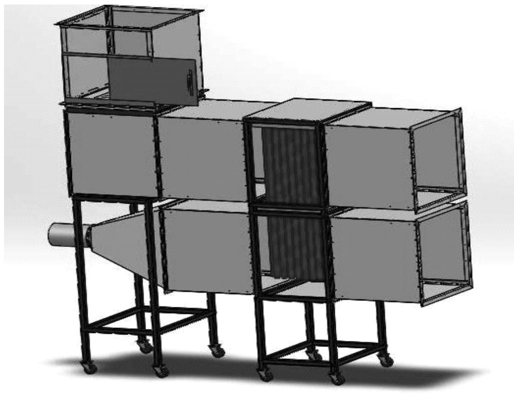

Figure 2 Hot air dryer using Thermosyphon heat pipe heat exchanger

Hot air dryer using a Thermosyphon heat pipe heat exchanger was used for drying paddy. The dryer consists of hot air tube blower set and drying chamber (Figure 2). The drying chamber is constructed of polycarbonate sheets with dimensions of 0.5 m wide × 0.5 m long × 0.5 m high. The dryer was combined with a set of Thermosyphon heat pipe heat exchanger. The paddy (San-Pah-Tong 1) was spread in a thin layer on screen trays with the dimension of 0.5 m wide × 0.5 m long × 0.2 high. The thickness of paddy was varied at 5, 10 and 15 cm. The drying temperature was controlled at 45±5°C for the whole drying period. During each experiment the sample was taken out every hour to determine its moisture content. The temperature of samples was also measured continuously using type-K thermocouples, which were inserted in the bed of the paddy.

Table 1 Parameters.

Parameters	Description
Dimensions of tube	D_o=30 mm, D_i= 25 mm and L_{tubes}=1100
Thermosyphon arrangement	Staggered, SL=55 mm and ST=55 mm
Number of rows	nL=7, nT= 8
Total of tube	N=53
Material	Seamless steel tube
Working fluid	Water
Paddy variety	San-Pah-Tong 1
Rice thickness	5 , 10 and 15 cm
Temperature of Drying chamber	45±5°C
Initial moisture content of paddy	34.57% wet basis
Final moisture content of paddy	14% wet basis

3. Open sun drying method

The paddy was placed in a tray with the varied thickness of paddy at 5, 10 and 15 cm. The sample was exposed to the sun for 12 h. During each experiment the sample was taken out every 5 h to determine its moisture content. The temperature of samples was also measured continuously using type-K thermocouples, which were inserted in the bed of the paddy.

4. Mathematical modeling

The moisture ratio (MR) of the paddy was defined as follows: $$MR=\frac{M_t-M_e}{M_i-M_e} \quad (1)$$

Where M_t, M_i and M_e are the moisture content at any time of drying (kg water/kg dry mass), initial moisture content (kg water/ kg dry mass) and equilibrium moisture content, respectively. The experimental data at different thicknesses of paddy were fitted into 5 thin-layer drying models that commonly used in most food and biological materials as shown in (Table 2).

Table 2 Mathematical models applied the moisture ratio

Model name	Model	Ref.
1. Henderson and Pabis	$MR = a\ exp\ (-kt)$	[11]
2. Midilli et al.	$MR = a$ exp($-kt$)+bt	[12]
3. Page	MR = exp($-kt^n$)	[13]
4. Modified Page	MR = exp(($-kt$)^n)	[14]
5. Logarithmic	MR = a exp(-kt)+c	[15]

5. Correlation coefficients and error analyses

The determination of coefficients (R^2), reduced chi-square (χ^2) and root mean square error (RMSE) were used to evaluate the goodness fit. These parameters were calculated as follows:

where N is the number of observations, z is the number of constants, $MR_{i,exp}$ and $MR_{i,pre}$ are the experimental and predicted moisture ratios, respectively.

6. Determination of effective moisture diffusivity

The drying characteristics of agricultural products in a falling rate period can be described by using Fick's second law of diffusion equation. The paddy is determined to be a sphere. Negligible shrinkage, constant diffusion coefficients and temperature during drying are assumed as follows:

In the case where t is large and R is small, terms in series where n>1 are negligible and Eq. (5) can be further simplified to

The effective moisture diffusivity is determined by plotting the experimental drying data in terms of ln (MR) versus drying time. A plot of ln (MR) versus drying time gives straight line with a slope as follows:

Results and Discussion

1. Drying characteristics of paddy

The average initial moisture content of the samples (San-Pah-Tong 1) prior to drying was approximately 34.57 (wet basis). Figure 3 shows the drying curves of the samples undergoing hot air drying using a Thermosyphon heat pipe heat exchanger and open sun drying at various thicknesses of paddy. It was observed that hot air drying using the Thermosyphon heat pipe heat exchanger exhibited higher drying rate than open sun drying, as expected. Drying at higher temperatures led to higher moisture diffusivity values and larger driving force for heat and mass transfer than at lower temperatures. Time needed to reach the desired moisture content of less than 14% wet basis is shown in (Table 3). The results showed that the paddy drying using Thermosyphon heat pipe heat exchanger provided 3.5 times higher in average drying rate than that using open sun. The layer thickness of 5 centimeters was found to be shorter in drying time than 10 and 15 centimeters. In addition, the results showed that hot air drying using Thermosyphon heat pipe heat exchanger took shorter drying time than open sun drying. Moreover, increase in thickness of paddy led to longer drying time, as expected.

Table 3 Time to dry samples to the final moisture content of less than 14% wet basis

Drying method	Layer thickness (cm)	Drying rates (g/hr)
Thermosyphon heat pipe heat exchanger	5	0.26
	10	0.24
	15	0.17
Open sun	5	0.09
	10	0.07
	15	0.04

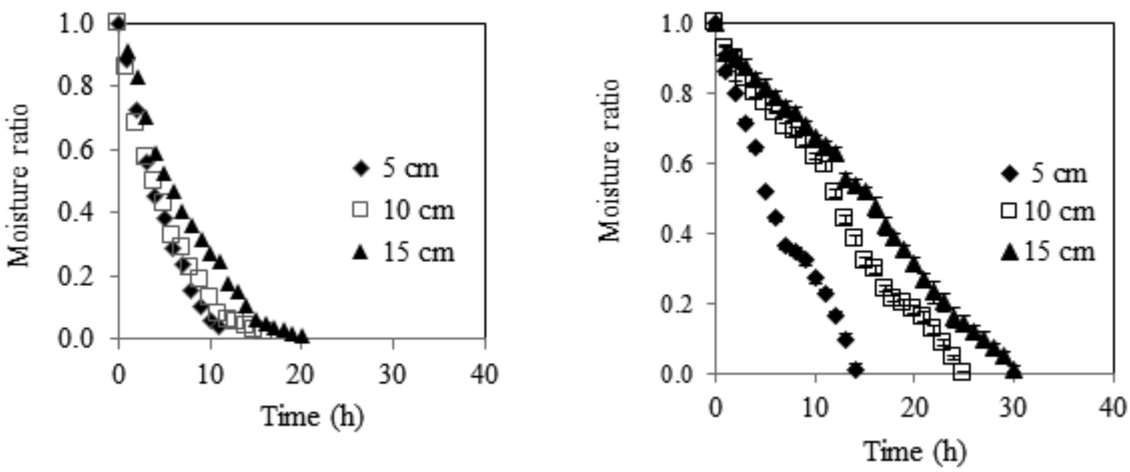

Figure 3 Drying curves of paddy dried by (a) hot air drying using Thermosyphon heat pipe heat exchanger and (b) open sun drying

2. Mathematical modeling of drying curves

Drying curves of the paddy under hot air using heat pipe heat exchanger was fitted with five different moisture ratio models shown in (Table 2). The statistical results of the different models, including the drying model coefficients and the comparison criteria used to evaluate goodness of fit, namely, R^2, χ^2 and RSME, are summarized in (Table 4). It can be seen that, the R^2 values for the models were in the range of 0.993-0.999, $\chi2$ values were varied between 0.0002 and 0.004 and, and RMSE values between 0.014 and 0.044. By comparing the criteria values among five drying models, it can be seen that Logarithmic was the best descriptive model for drying methods, since it exhibited the highest average value of R^2, the lowest average values of $\chi2$ and RMSE. Thus, it was selected to represent the drying charac teristics of paddy.

3. Determination of effective moisture diffusivities

The values of the effective moisture diffusivity values are calculated using Eq.6 and 7 and were found to range between 2.11×10^{-8} m^2/s and 1.37×10^{-7} m^2/s (shown in Table 5). The effective moisture diffusivity was affected by drying method and thickness of paddy. It was observed that the increase in Deff in paddy affected the thickness of paddy increased. Similar results have previously been reported. Rasouli et al.[16] and Yardfon et al.[17], for example, found that higher thickness of samples resulted in larger effective moisture diffusivity.

Table 4 Statistical results obtained from different drying models

Model name	Drying method	Thickness	Drying Constants	R^2	χ^2	RSME
1.Henderson and Pabis	Thermosyphon	5 cm	k=0.220, a=1.059	0.994	0.0016	0.037
		10 cm	k=0.195, a=1.027	0.997	0.0007	0.025
		15 cm	k=0.145, a=1.058	0.994	0.0014	0.035
2.Midilli et al.	Thermosyphon	5 cm	k = 0.228, n=0.894, a=1.126, b= -0.011	0.996	0.0021	0.037
		10 cm	k = 0.169, n=1.017, a=1.004, b= -0.003	0.998	0.0003	0.014
		15 cm	k = 0.130, n=0.972, a=1.051, b= -0.005	0.998	0.004	0.019
3. Page	Thermosyphon	5 cm	k=0.132, n=1.271	0.998	0.0003	0.017
		10 cm	k=0.151, n=1.121	0.998	0.0004	0.019
		15 cm	k=0.085, n=1.219	0.997	0.0006	0.023
4. Modified Page	Thermosyphon	5 cm	k=0.183, n=1.129	0.993	0.0021	0.044
		10 cm	k=0.152, n=1.245	0.996	0.0008	0.026
		15 cm	k=0.138, n=0.987	0.993	0.0018	0.041
5.Logarithmic	Thermosyphon	5 cm	k=0.146, a=1.242 c=-0.220	0.999	0.0003	0.015
		10 cm	k=0.161, a=1.079 c=-0.077	0.998	0.0002	0.014
		15 cm	k=0.104, a=1.167 c=-0.150	0.998	0.0003	0.017

Table 5 Effective moisture diffusivity values of paddy

Drying method	Layer thickness (cm)	D_{eff} (m^2/s)
Hot air using Thermosyphon heat pipe heat exchanger	5	2.11×10^{-8}
	10	7.09×10^{-8}
	15	1.37×10^{-7}

Conclusion

The experiments were performed to determine drying characteristics of paddy cv. San-Pah-Tong 1 dried by hot air drying using a Thermosyphon heat pipe heat exchanger and open sun drying method. According to the statistical analysis applied to all models, it can be concluded that among these models, Logarithmic gave the best results. In addition the drying method, thickness of paddy had a significant influence on the drying rate. Hot air drying using Thermosyphon heat pipe heat exchanger required shorter drying time than open sun drying since drying rate of hot air drying was higher than that of open sun drying. Increase in thickness of paddy resulted in decreased drying rate and needed longer drying time to reach the final moisture content. Moreover, drying method and thickness of paddy affected the effective moisture diffusivity values of paddy. Studies on physical and nutritional properties of the paddy after drying are suggested as a future work.

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