Design and Testing of Solar Dryer for Drying Kinetics of Seaweed in Malaysia

A. Fudholi, M. Y. Othman, M. H. Ruslan, M. Yahya, A. Zaharim and K.Sopian

Abstract— A forced convection drying system is designed and installed at the Green Energy Technology Innovation Park, Universiti Kebangsaan Malaysia, Selangor, Malaysia. The main components of the system are double-pass solar collector with finned absorber, the blower, the auxiliary heater and the drying chamber. The solar drying system is tested for drying kinetics of seaweed. The initial and final moisture content of the seaweed are 94.6% (wet basis) and 10% (product basis) respectively. The drying time is about of 7 hours at average solar radiation of about 600 W/m^2 and air flow rate 0.0613kg/s. A excel software is used in the analysis of raw data obtained from the drying experiment. The values of the parameters a, n and the constant k for the models are determined using a plot of curve drying models. Three different drying models are compared with experiment data at average temperature and relative humidity about 50^{o}C and 20% respectively. The most suitable model is selected to best describe the drying behavior of seaweed. The values of the coefficient of determination (R^2), mean bias error (MBE) and root mean square error (RMSE) are used to determine the goodness or the quality of the fit. The Page model is showed a better fit to drying seaweed among Newton model and Henderson and Pabis model.

Keywords— Solar drying system, drying kinetics, drying modeling, seaweed.

I. Introduction

MALAYSIA is located in the equatorial region. Malaysia is located between 1.30^o North to 6.60^o North longitude and 99.50^o East to 103.30^o East latitude. Malaysia typically receives about 13 hours of solar radiation. The average solar radiation is 4-5 kWj/m^2, while the average number of hours of irradiation of between 4 to 8 hours, the average temperature is around 26 to 32^{o}C and the average relative humidity of 80 to 90% and never falls below 60% (Othman et al. 1993). In Malaysia, there is an increase in the mean daily global solar radiation. In the early 1990 about the value will rise to 4.5 kWj/m^2 (Sopian 1992), and added value rose again to a level 5.0 kWj/m^2 through research done by using satellite imaging (Azhari et al. 2008). Therefore, the use of solar drying system has a potential with the climate of Malaysia. An analysis of solar radiation at several main towns in Malaysia shows that solar radiation is possible to be used in solar drying (Sopian 1992).

Solar drying system is one of the most attractive and promising applications of solar energy systems in tropical and subtropical countries. The technical development of solar drying systems can proceed in two directions. Firstly, simple, low power, short life, and comparatively low efficiency-drying system. Secondly, high efficiency, high power, long life expensive drying system (Fudholi et al., 2010).

Many studies on the performance of solar drying system have been conducted in the Green Energy Technology Innovation Park, Universiti Kebangsaan Malaysia, such as solar assisted drying systems with V-groove solar collector, the double-pass solar collector with integrated storage system, the solar assisted dehumidification system for medicinal herbs and the photovoltaic thermal (PVT) collector system (Othman et al ., 2006).

The objective of this study is to propose mathematical model for the drying curves of seaweed.

II. Material and Methods

The experiments are carried out at the Green Energy Technology Innovation Park, Universiti Kebangsaan Malaysia.

A. Description of Solar Drying System

Fig.1 shows the schematic diagram of the experimental setup. The main components are solar collector array (Fig. 2), auxiliary heater, blower, and drying chamber. The size of the chamber is 4.8 m in length, 1 m width and 0.6 m in height. The collectors are the double-pass finned collector. The four collectors are set in series. The double-pass finned collector efficiency is about of 38-78% (Fudholi et al. 2010).

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A. Fudholi, M. Y. Othman, M. H. Ruslan, M. Yahya, A. Zaharim and K.Sopian is with the Solar Energy Research Institute, Universiti Kebangsaan Malaysia, 43600 Bangi Selangor, MALAYSIA.
(E-mail: fudholi.solarman@gmail.com, azami.zaharim@gmail.com, ksopian@eng.ukm.my)

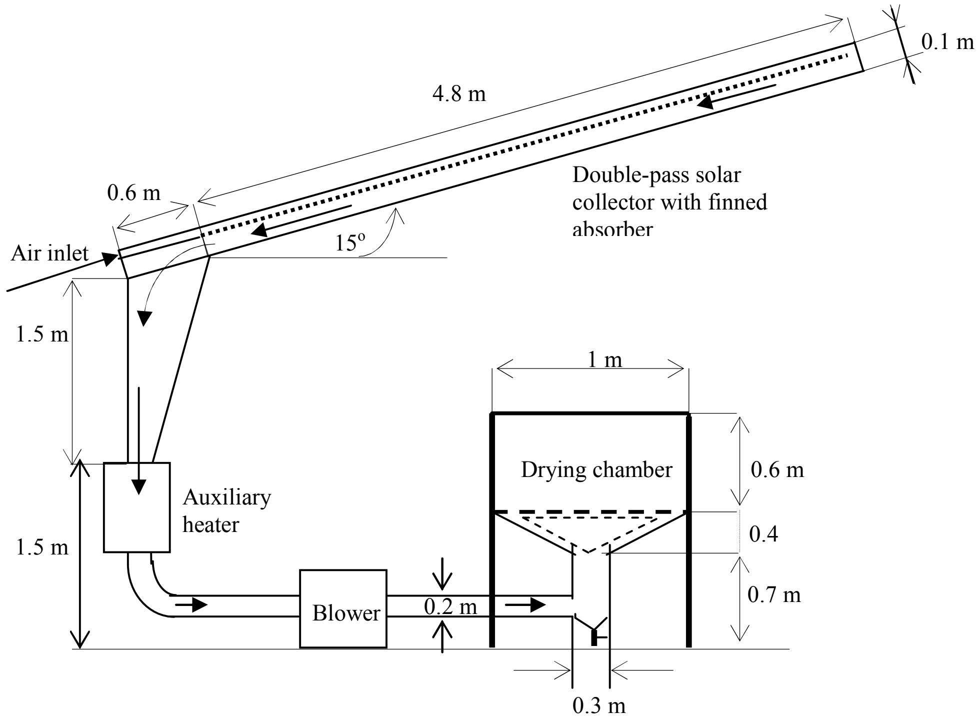

Fig. 1. Schematic diagram of solar drying system

The collector width and length were 1.2 m and 4.8 m respectively. The solar collector array consists of 4 solar collectors. The upper channel depth is 3.5 cm and the lower depth is 7 cm. The bottom and sides of the collector have been insulated with 2.5cm thick fiberglass to minimize heat losses. Table 1 shows key parameters of the solar drying system.

Fig. 3 shows the cross section of the collector with the aluminium plate fins. The collector consists of the glass cover, the insulated container and the black painted aluminium absorber. The size of the collector is 1.2 m wide and 4.8 cm long. In this type of collector, the air initially enters through the first channel formed by the glass covering the absorber plate and then through the second channel formed by the back plate and the finned absorber plate.

Table 1. Key parameters of the solar drying system

Parameters	Unit	Value
Collector area	m^2	11.52
Drying chamber area	m^2	4.8
Capacity of dryer	kg	150-200
Mass flow rate	kg/s	0.05-0.13
Average drying air temperature	^oC	40-65

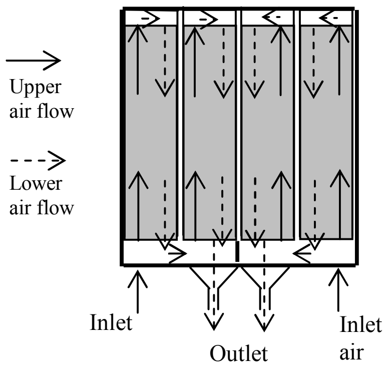

Fig. 2. The collector arrangement for the solar drying system

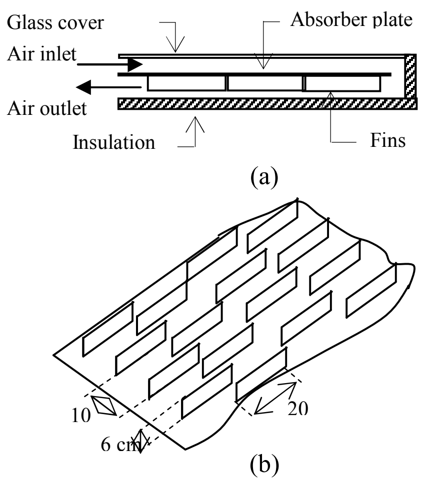

Fig. 3. (a) The schematic of a double-pass solar collector with fins absorber in the second channel and (b) top view of the staggered finned absorber.

A. Method

Experiment done begins at 08:00 am that day at 06:00 pm, which begins when the data was taken from 09:00 am to 05:00 pm. The data measured are air temperature (ambient temperature, air temperature inlet and outlet of the collector), radiation intensity and air velocity, also measured the air temperature before it enters the dryer chamber, the temperature inside the dryer chamber, the temperature of the air out of the dryer chamber and wet bulb temperature and dry bulb temperature of the air out of the dryer chamber. Air temperature was measured by T-type thermocouple is then recorded in a data acquisition system. The intensity of solar radiation measured by pyranometer and measurement data recorded in a computer.

B. Data Analysis

The thermal efficiency of a solar collector is the ratio of useful heat gain to the solar radiation incident on the plane of the collector. It is defined as (Fudholi et al. 2011)

$$\eta_c = \frac{mC(T_o - T_i)}{A_c I} x100\% \qquad (1)$$

where,
m = mass flow rate (kg/s)
C = specific heat of air (J kg^{-1} $^oC^{-1}$)
A_c = collector area (m^2)
T_i = inlet air temperature (^oC)
T_o = outlet air temperature (^oC)
I = solar radiation intensity (W/m^2)

To determine the kinetics of drying seaweed, drying model is used. Table 2 shows there are some drying models.

Table 2. Several models of drying (Aktas et al. 2009; Ibrahim et al. 2009)

No.	Model name	Model
1	Newton	MR = exp(-kt)
2	Page	MR = exp(-kt^n)
3	Modified Page	MR =exp(-$(kt)^n$)
4	Henderson and Pabis	MR = a exp(-kt)

The moisture ratio (MR) can be calculated as (Ibrahim et al. 2009)

$$MR = \frac{M - M_e}{M_0 - M_e} \qquad (2)$$

where,
Me = Equilibrium moisture content
Mo = Initial moisture content

The moisture content of materials (M) can be calculated by two methods on the basis of either wet or dry basis using the following equation. The moisture content wet basis

$$M = \frac{w(t) - d}{w} x100\% \qquad (3)$$

The moisture content dry basis (Dissa et al. 2009)

$$X = \frac{w(t) - d}{d} \qquad (4)$$

where,
w(t) = mass of wet materials at instant t
d = mass of dry materials

The value of initial moisture seaweeds need to know before drying done in the solar drying system. The study of seaweed drying using Low Temperature Test Chamber and Humidity in the Solar Energy Laboratory, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, instead of seaweed drying tests found it had an initial moisture content of 94.6%.

The values of the coefficient of determination (R^2), mean bias error (MBE) and root mean square error (RMSE) are used to determine the quality of the drying model. The highest R^2 values and the values of MBE and the lowest RMSE are selected to estimate the drying curve is the best (Ibrahim et al. 2009).

$$MBE = \frac{1}{N}\sum_{i=1}^{N}\left(MR_{pre,i} - MR_{\exp,i}\right)^2 \qquad (5)$$

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

III. Results and Discussion

Experiments carried out starting at 08:00 am today so at 6:00 pm, the time data were taken beginning at 09:00 am till 05:00 pm. Fig. 4 shows experimental results of drying seaweed which in sunny weather, obtained dryer chamber temperature range around 30°C<T<65, an average temperature chamber about 50°C and average relative humidity about 20%.

From Fig. 5, obtained the efficiency of collector varies from 20 to 44% and the average efficiency of collector about 31%.

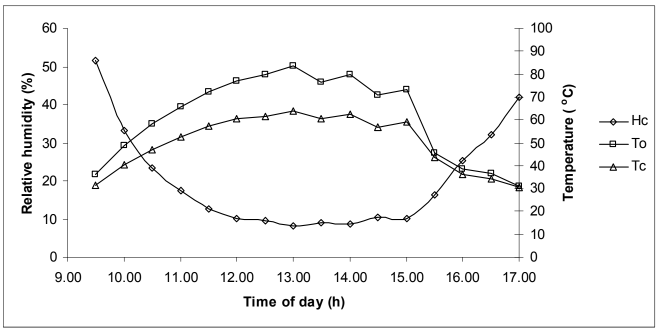

Fig. 4. Air temperatures and relative humidity of drying chamber at various time of day

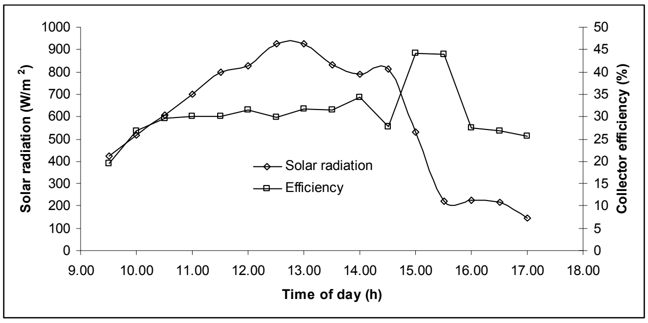

Fig. 5. Solar radiation and efficiency of collector at mass flow rate 0.0613 kg/s

Drying of seaweed in the Green Energy Technology Innovation Park using a solar drying system using double-pass solar collector with finned absorber takes 7 hours to reduce the initial moisture content of 94.6% to 8.33% equivalent to 120 grams to 11 grams. Drying process on the average solar radiation about 600W/m^2 and drying air flow rate 0.0613kg/s. Change in mass was recorded every 15 minutes. Fig. 6 shows the change in mass with time, the mass of seaweed was found to decline with time. Fig. 7 shows decreased moisture content wet basis of drying time.

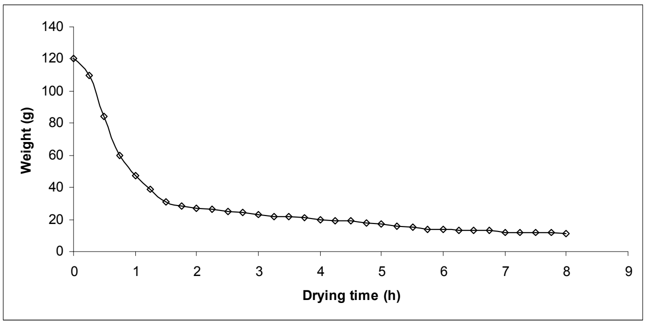

Fig. 6. Weight variation with drying time

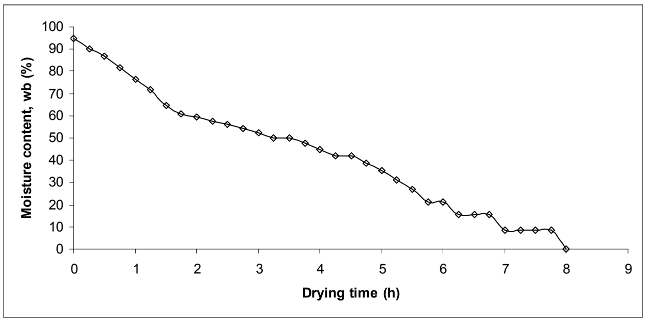

Fig.7. Moisture content variation with drying time

Fig. 8 to Fig. 10 shows kinetic curves of drying seaweed at 50^{o}C and relative humidity of 20%. It consists of three curves of the drying curve, the drying rate curve and the characteristic drying curve. Drying curve shows the profile change in moisture content (X) versus drying time (t). Drying rate curve shows the drying rate profile (dX/dt) versus drying time (t). Drying characteristic curves showed that the drying rate profile (dX/dt) versus moisture content dry basis (X).

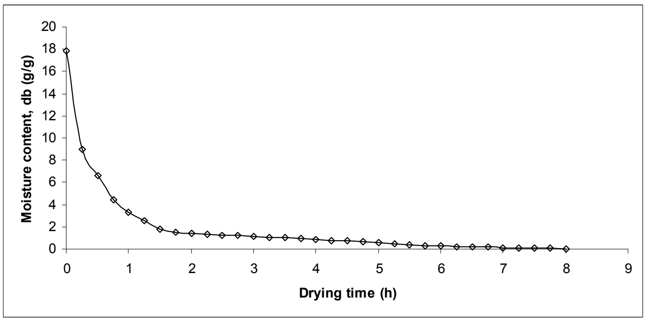

Fig. 8. Drying curve: dry basis moisture content versus drying time

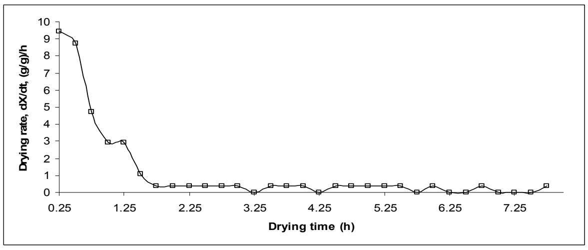

Fig. 9. Drying rate curves: dry basis moisture content versus drying time

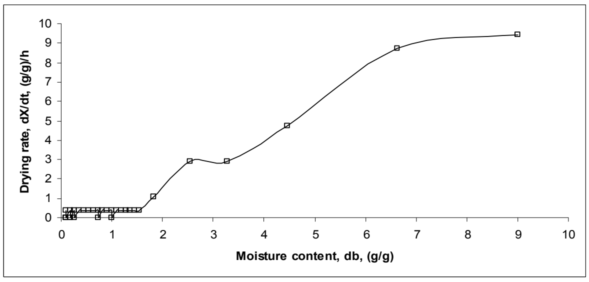

Fig. 10. Drying characteristic curves: a dry basis moisture content versus drying time

Fitting some of the drying model has been done with the experimental data of drying seaweed solar dryer system at an average temperature of 50°C chamber, and the average relative humidity 20%. Drying models are fitted with the experimental data of drying is the drying of the Newton model, Page model drying, and drying model and Pabis Henderson. Drying experimental data fitted the model of drying in the form of changes in moisture content versus drying time. In this drying models, changes in moisture content versus time calculated using Excel software.

Table 3 shows the result matched the drying models with experimental data of drying. From Table 1 showed a constant drying and accuracy of fitting each model of drying. R^2 is the highest and the MBE and the lowest RMSE is selected to estimate the drying curve is the best (Ibrahim et al. 2009).

Page equation can also be written to the equation:

$$\ln(-\ln MR) = \ln k + n \ln t \qquad (7)$$

Equation 7 is the relationship ln (-ln MR) versus t, is the curve of the logarithmic equation, as sketched in Figure 12. Henderson and Pabis equation can also be written by equation

$$\ln MR = -kt + \ln a \qquad (8)$$

From equation 8, a plot of ln MR versus drying time gives a straight line with intercept = ln a, and slope = k. Graf MR versus ln t, as shown in Fig. 13, obtained the value k = 0.6289 and the value of a = 0.4138

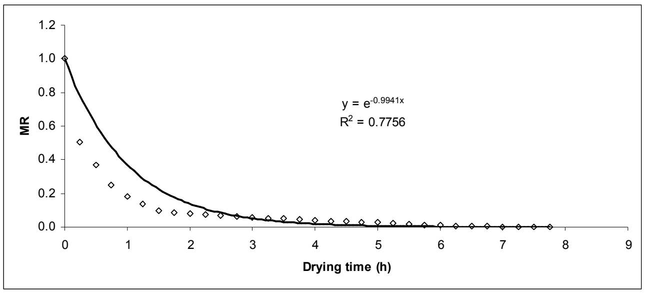

Fig. 11. Plot of MR versus drying time (Newton's model)

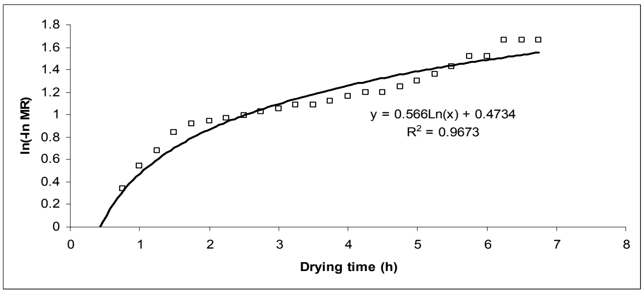

Fig. 12. Plot of ln (-ln MR) versus drying time (Page's model)

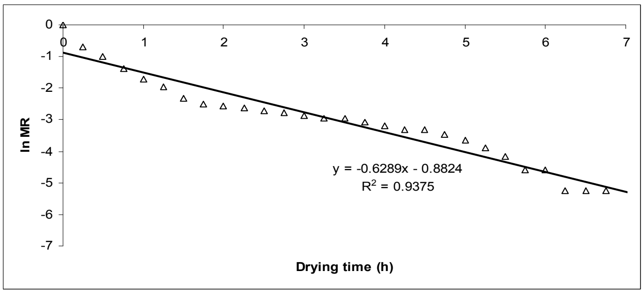

Fig. 13. Plot of ln MR versus drying time (Henderson and Pabis model)

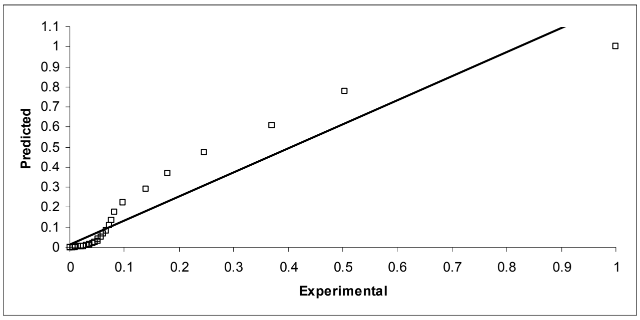

Fig.14. Comparison of experimental MR with predicted MR from Newton model

Fig.15. Comparison of experimental MR with predicted MR from Page model

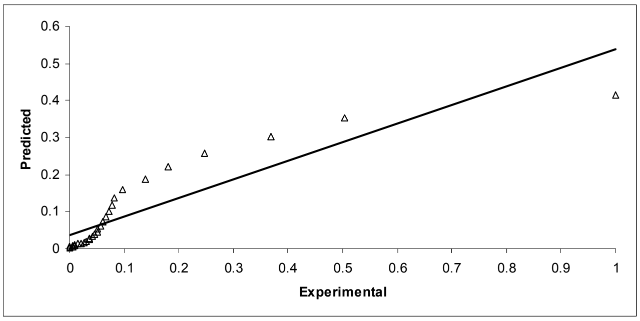

Fig.16. Comparison of experimental MR with predicted MR from Henderson and Pabis model

Table 2. Constant value matches some of the drying model

Model	a	K	n	R^2	MBE	RMSE
Newton		0.9941		0.7756	0.0087	0.0933
Page		1.6054	0.566	0.9673	0.0002	0.0139
Henderson & Pabis	0.4138	0.6289		0.9375	0.0120	0.1098

Results are given in Table (2) shows the Page drying model has the highest value of R^2, as well as the values of MBE and RMSE is the lowest compared to Newton's model of drying and drying model and Pabis Henderson, so seaweed drying model is a model suitable drying Page. Fig. 14 to Fig. 16. shows comparison of experimental MR with predicted MR from models drying. Fig 14 shows the distribution of experimental values in the vicinity of the straight line shows the expected value.

I. Conclusions

A solar drying system using double-pass solar collector with finned absorber is tested on samples of seaweed. Kinetic curves of drying of seaweed are known to use this system. From the study, seaweed drying process using this system has taken over a period of 7 hours for the initial moisture content 94.6% to 8.33% equivalent to 120 grams to 11 grams. When the decreasing rate period is assumed to occur only a single exponential equation, the equation is the equation of drying according to the Page model equation MR = exp $(-1.6054t^{0.566})$ with 96.7% accuracy.

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