วิศวกรรมสาร มข. ปีที่ 34 ฉบับที่ 2 (243 - 250) มีนาคม – เมษายน 2550 บทความวิจัย
KKU Engineering Journal Vol. 34 No .2 (243 - 250) March – April 2007

Forced Convection Solar Drying: Experimental Investigation and Mathematical Modeling of Pork Strips*

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ABSTRACT

Due to being a renewable energy, solar energy is widely used to numerous applications, especially the drying process. An indirect forced convection solar dryer with a solar air heater was developed and tested in this study. Comparative experiments between solar and open sun drying of pork strips were carried out. Moisture ratios were fitted to five different mathematical models using non-linear regression analysis. Color of the dried products was also measured. The experimental results showed that to obtain the same final moisture content, open sun drying required 1.5 times longer drying period than the solar drying. The Page model was found to be most accurate for describing the solar drying curves of the two drying methods, with high coefficient of determination (R^2) and low chi-square (χ^2) and RMSE. Analyses of color revealed that pork processed by solar drying was more reddish and yellowish than that processed by open sun drying.

Keywords : Pork, Solar drying, Sun drying

* Original manuscript submitted: January 12, 2007 and Final manuscript received: March 3, 2007

INTRODUCTION

Solar energy is abundant for the countries located in the tropical region. There are several ways for application of solar energy and one of them is drying process. Reviews in literature shows that solar and direct sun drying methods have been utilized to dry numerous agricultural products e.g., grape (Fadhel A.,*et al*.,2005), pineapple (Bala B.K., *et al*.,2003), apricot (Togrul I.T. and Pehlivan D,2002), pumpkin (Sacilik K., 2007), cassava, banana, mango (Toure S. and Kibangu-Nkembo S., 2004), pepper, garlic (Condorı´ M., *et al*.,2001), and rice (Basunia M.A. and Abe T., 2001). Compared to natural sun drying, solar drying was stated to be able to shorten drying time and the quality of the dried products can be improved in terms of hygiene, cleanliness, color and taste (Sacilik K., 2007). It is noted from reviews of literature that though a great deal of research work has been conducted on solar drying of crops, limited attempt has been done on the drying of meat. The present study therefore focuses on the study of solar drying of pork meat using a developed forced convective solar dryer. Drying characteristics and color of the meat processed by solar drying was compared to those processed by direct sun drying. Mathematical models were also tested to fit the drying data.

MATERIALS AND METHODS

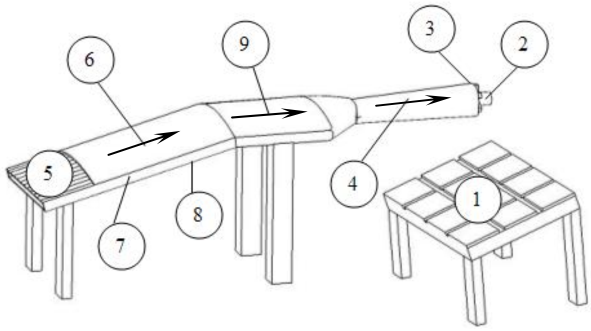
Raw materials

Pork meat was purchased from a local supermarket and it was cut into strips with dimensions of 1 cm×20 cm×0.5 cm. The initial moisture content of the meat determined by the air oven drying method (AOAC, 1995) was 292% d.b.

Drying procedure

Drying experiments were conducted in the solar dryer, as shown in Fig. 1. The solar air collector is 60 cm×100 cm in dimension. It is southward oriented at the angle of 13^o. A corrugated black zinc sheet was used as an adsorber plate. A plastic sheet was used as a transparent cover to avoid heat losses. The fan powered by PV modules sucks the heated air through the 0.0265 m^3 drying cabinet.

Twenty kilograms of pork placed on a wire mesh tray was loaded into the drying chamber. Drying experiments were performed in February 2004. Inlet and outlet air temperatures, air velocity, and solar radiation were monitored and recorded. Water loss from the samples was determined by weighing the sample tray outside the drying chamber every 5 minutes, using an electronic balance (±0.01 g). Open sun drying process was carried out by placing pork meat in trays and sun dried directly. The experiments were conducted in duplicated.



1. Solar cell	2. ¼ hp Motor	3. Axial flow fan
4. Air duct	5. Black zinc plate	6. Solar collector
7. Air duct	8. Insulator	9. Drying chamber

Fig. 1 *Indirect forced convection solar dryer with a solar air heater*

Drying kinetics

To predict the drying curves of pork processed by both solar and open sun drying, the moisture content measured were transformed to the moisture ratio (MR) by using eq. 1 and the moisture ratio were then fitted to six mathematical models. These models were tabulated in Table 1.

$$MR = \frac{M(t) - M_e}{M_i - M_e} \tag{1}$$

Model name	Models
Newton	MR=exp(-*k*t)
Page	MR=exp(-*k*t^n)
Henderson and Pabis	MR=*y*exp(-*k*t)
Two term exponential	MR=yexp(-*k*t)+(1-*y*)exp(-kyt)
Diffusion approximate	MR=*y*exp(-*k*t)+(1-*y*)exp(-kzt)
Wang and Singh	MR=1+*y*t+zt^2

Table 1 *Mathematical models used to describe the drying characteristic of pork strips*

where MR = moisture ratio (decimal)
M(t) = moisture content at anytime (% d.b.)
M_i = initial moisture content (% d.b.)
M_e = equilibrium moisture content (% d.b.)
t = time (min)
y, *z*, *k* and *n* = constants

The equilibrium moisture content used to calculate MR was determined using the standard static gravimetric method developed by the European Cooperative Project COST 90. Parameters of the drying models were estimated from the experimental results using the nonlinear regression analysis. The adequacy of the fit obtained by using the six models to simulate the experimental data, was evaluated by the coefficient of determination (R^2), the root mean square error (RMSE) and the chi-square (χ^2). RMSE and χ^2 are defined as:

$$\mathrm{RMSE} = \left[\frac{1}{N} \sum_{i=1}^{N} (X_{pre,i} - X_{exp,i})^2 \right]^{1/2} \tag{2}$$

$$\chi^2 = \frac{\sum_{i=1}^{N} \left(X_{exp,i} - X_{pre,i} \right)}{N - n} \tag{3}$$

where $X_{exp,i}$ is the moisture content obtained from the experiment and $X_{pre,i}$ is the moisture content predicted by the models. N and n are the number of observations and the number of constants respectively.

Color measurement

Surface colors of dried pork meat were measured by a colorimeter (Mini scan ex plus). The color system used was Hunter Lab where "L" represents lightness, "a" represents redness (+) or greenness (-), and "b" represents yellowness (+) or blueness (-). The colorimeter was calibrated against a standard white plate. The color measurements were performed on 10 samples and the average values were reported.

RESULTS AND DISCUSSION

Solar Radiation

Intensity of the solar radiation measured, using a pyranometer (Sanwa, Japan), during the drying process is shown in Fig. 2. It was noticed that for the experiment conducted at 1 P.M., the direct radiation was rather fluctuated. This was probably because in the morning the sky was clear while in the afternoon the sky was partly cloudy.

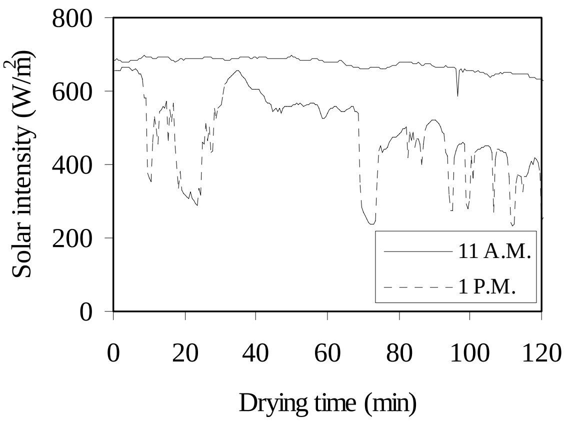


Fig. 2 *Intensity of the direct solar radiation*

Drying kinetics

The moisture ratio of pork strips and drying time is illustrated in Fig. 3. The drying kinetics was found to be strongly influenced by the drying method used. Solar drying gave the faster moisture reduction rate than the open sun drying. This was because the temperature of the product dried by solar drying was higher than that dried by open sun drying (see Fig. 4). The higher drying temperature induced higher moisture diffusion rate, corresponding to Arrhenius's equation, resulting in the faster moisture removal rate.

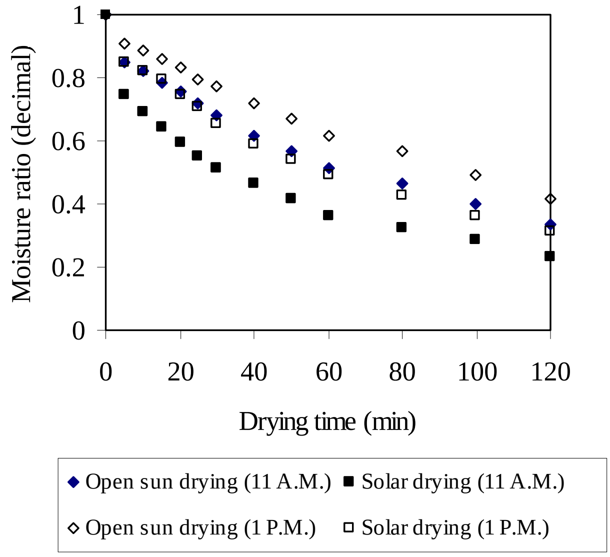


Fig. 3 *Drying characteristics of pork strips undergoing open sun and solar drying*

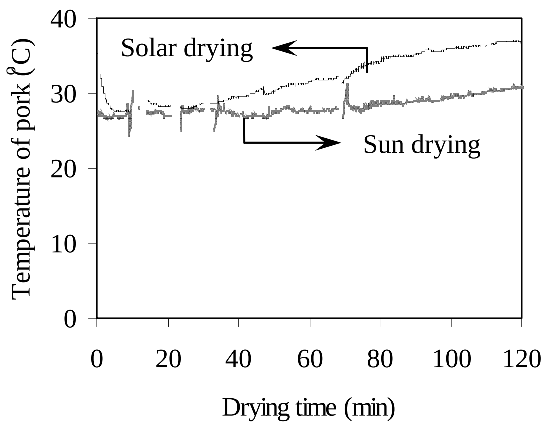


Fig. 4 *Temperature evolution of pork strip during solar and sun drying at 11 A.M.*

Model	Constant	Solar drying		Open sun drying	
		11 A.M.	1 P.M.	11 A.M.	1 P.M.
Newton	k	0.01873	0.01185	0.01086	0.00777
	R^2	0.77918	0.93884	0.91644	0.97427
	RMSE	0.00929	0.00240	0.00287	0.00072
	χ^2	0.01007	0.00260	0.00310	0.00078
Page	k	0.10704	0.03547	0.03789	0.01637
	n	0.53812	0.72726	0.69178	0.82139
	R^2	0.99734	0.99410	0.99301	0.99470
	RMSE	0.00011	0.00023	0.00024	0.00015
	χ^2	0.00013	0.00027	0.00028	0.00018
Henderson and Pabis	a	0.83325	0.92209	0.91417	0.95927
	k	0.01336	0.01006	0.00897	0.00700
	R^2	0.91123	0.97811	0.97346	0.99200
	RMSE	0.00374	0.00086	0.00091	0.00022
	χ^2	0.00442	0.00102	0.00108	0.00027
Two term exponential	a	0.16424	0.12810	0.11699	0.06299
	k	0.08948	0.07352	0.07456	0.10581
	R^2	0.89045	0.98298	0.97340	0.99496
	RMSE	0.00461	0.00067	0.00094	0.00014
	χ^2	0.00545	0.00079	0.00111	0.00017
Diffusion approximate	a	0.29426	0.10925	0.11884	0.05451
	k	0.21740	1.11882	0.77797	0.95437
	b	0.04514	0.00837	0.01061	0.00706
	R^2	0.99317	0.99480	0.99626	0.99808
	RMSE	0.00029	0.09786	0.81419	0.07009
	χ^2	0.00037	0.12722	1.05844	0.09113
Wang and Singh	a	-0.0178	-0.0125	-0.0118	-0.0083
	b	0.00010	0.00006	0.00006	0.00003
	R^2	0.81528	0.96116	0.94595	0.98089
	RMSE	0.00778	0.00153	0.00185	0.00054
	χ^2	0.00919	0.00181	0.00219	0.00063

* Time shown in the table is the time at which the drying process started

Table 2 *Estimated parameters and statistical data of the mathematical models fitted to the drying curves of pork*

Six different mathematical models were fitted with the drying data and estimated parameters and statistical data obtained are shown in Table 2. It was clearly seen that for both drying methods, Page model gave the highest value of R^2 and the lowest values of RMSE and χ^2. This indicated that in this study, Page model was the most suitable model for describing the drying curves of pork strips.

Validation of the drying models in Fig. 5 shows that most of the models tended to over predict at the early stage of drying and under predict at the late stage of drying. Model validation for the case of open sun drying was similar to that for the case of solar drying (not shown).

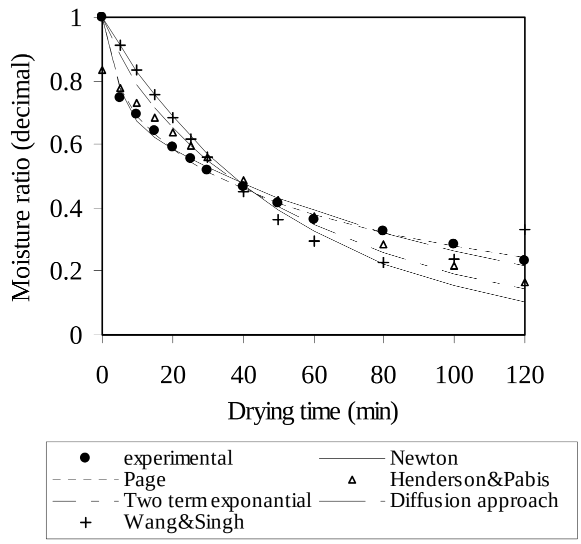


Fig. 5 *Fitting the six mathematical models to the solar drying curve (11 A.M.)*

Color parameters, expressed by L, a, and b, of pork strips dried at different times and methods are tabulated in Table 3. Lightness of pork dried by different drying conditions was not much different. On the contrary, redness and yellowness showed significantly different values. Solar drying yielded more reddish and yellowish products than open sun drying. This may be attributed to the higher product temperature in the case of solar drying.

Drying method	L	a	b
Solar drying (11 A.M.)	28.23±0.007	6.16±0.0239	10.37±0.025
Open sun drying (11 A.M.)	28.75±0.826	4.89±0.141	8.51±0.134
Solar drying (1 P.M.)	29.08±0.013	6.18±0.047	10.11±0.037
Open sun drying (1 P.M.)	28.53±0.025	5.01±0.015	9.02±0.034

* Time in the parenthesis is the time at which the drying process started

Table 3 *L, a, and b values of pork dried by solar and open sun drying*

CONCLUSIONS

Comparative study of open sun drying and force convective solar drying of pork strips was conducted and it was found that the drying rate of solar drying was faster than that of sun drying. Page model was found to adequately describe the drying taking place in both solar and sun drying. Pork meat undergoing solar drying was more reddish and yellowish than that undergoing open sun drying. Nevertheless, whiteness of the product dried by both methods was not significantly different.

ACKNOWLEDGEMENTS

The authors express their sincere gratitude to the Faculty of Engineering, Mahasarakham University for financial support. Thanks are given to Mr. Phethnarinth Imraksa and Mr. Weerachat Mapatung for collecting all the experimental data.

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