Drying Kinetics of Natural Rubber Sheets by Using a Hybrid Solar-Electric Dryer with Force Convection

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Abstract

In this work, a hybrid solar-electrical dryer was constructed for studying the drying kinetics of natural rubber sheets. This system composed of the solar collector, which used to collect heat from the sun light. The hot air from solar collector was sent to the drying chamber, where an auxiliary heater can increase the temperature in the drying chamber in order to control the drying temperature. The rubber sheets were dried at the controlled temperature 40 50 and 60 °C. The moisture ratio of rubber sheets drying was investigated. Seven models were tested to fit with the experimental data. A modified Henderson and Pabis model was the best of curve fitting of the drying behavior of rubber sheets in these specific experimental conditions. Finally, the consumptions of electrical energy and solar energy were determined, which is found in the range of 15-32% of the solar energy used.

Keywords : rubber sheets, drying kinetics, solar dryer, hybrid system

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1. Introduction

At the southern of Thailand, the abundant trees, which are grown by agriculturists to produce natural rubber latex, are natural rubber trees. Most of the agriculturists are a farm owner and the process that they make natural rubber sheets by using the natural rubber latex is the drying process, which drys them under the sun before delivery them to the natural rubber plants. At that place, natural rubber sheets are produced in four types: Ribbed smoked sheet (RSS), block rubber, rubber concentrated latex, and other. However, this method relies on favorable weather and the drying temperature is not controlled. Various types of dryer with different heat sources have been proposed, to gain improved control of sheet drying. In smokehouse drying, it needs to put a fire wood by workers, and pollution of burning firewood or biomass. Thus, alternative energy such as solar energy has been considered. Breymayer et al. [1] designed a simple solar assisted smokehouse for the drying natural rubber in Indonesian farms. Pratoto et al. [2] used solar energy combined with an auxiliary heater for drying a natural rubber. The drying kinetics of the slice tomato and the red seaweed named Gelidium sesquipedale were studied by Boughali et al. [3] and Mohamed et al. [4], respectively. Recently, the thermal modelling of the force convection sandwich greenhouse drying systems for rubber sheet was proposed [5]. The objective of this work was to investigate the drying kinetics of rubber sheets at the controlled temperature of 40 50 and 60 °C in a hybrid system with solar and also determined how much electrical energy can be saved with this system at the temperature 50 °C, because in rubber drying industrials, they use the drying temperature around 50°C in their process.

2. Experimental setup

2.1 Solar-Electrical Dryer

The schematic diagram of solar-electrical is shown in Fig.1. The solar collector has dimension of 140cm-length and 80cm-width. The dimension of the drying chamber is 80cm × 80cm × 80cm. The solar radiation was measured using solar power meter modeled DT-1307. Hot air was sent into the drying chamber by a fan and the temperature regulated to 40 50 and 60 °C, by a feedback loop controlling an electric heater after the fan. The six rubber sheets hung with a bamboo rod, which placed on the lever. The combined weight of rubber sheets was determined with 2 hook balances, within ± 10 g. The surface temperature of rubber sheets was measured using j-type thermocouples, while a k-type was used for measured the circulating air temperature in the chamber. In case of the temperature inside below the controlled temperature, an auxiliary heater will increase the temperature, then the hot air blew through the drying chamber. The moisture was evaporated at the bottom of the drying chamber.

2.2 Mathematical modelling

The moisture content *(MC)* was determined on dry basis following a standard method of Association of Official Analytical Chemists (AOAC), as shown in Eq.1. W_i is the initial weight and W_d is the dry weight, both of them were determined by 2 hooks balance.

The moisture ratio *(MR)* is calculated by using Eq.2. $M_{(t)}$ is sheet moisture at time t and M_{eq} is a equilibrium moisture. The equilibrium moisture is calculated by using Equation3. Here *A, B, C*, and *D* are constants, these parameters are calculated by following Ref. [6]. RH is relative humidity. T is a temperature in Kelvin. The drying kinetics of rubber sheets were fitted by using seven models from literatures, as shown in table 1.

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

$$MR = \frac{M_{(t)} - M_{eq}}{M_i - M_{eq}} \tag{2}$$

$$M_{eq} = \left[\frac{-A}{(BT + CT^2)\ln RH} \right]^{\frac{1}{D}} \tag{3}$$

Two statistical named χ^2 and R^2 were used to quantify the comparison between mathematical models and experiments. These two parameters were calculated by the Origin software version6 and they are defined as shown in the Eq.4. and Eq.5., respectively. [7]

$$\chi^2 = \frac{\sum_{i=1}^{n} (MR_{exp,i} - MR_{pre,i})^2}{N - n} \tag{4}$$

$$R^2 = \frac{\sum_{i=1}^{n} (MR_{pre,i} - \overline{MR}_{pre,i})^2}{\sum_{i=1}^{n} (MR_{exp,i} - \overline{MR}_{exp,i})^2} \tag{5}$$

where $MR_{pre,i}$ is moisture from prediction, and $MR_{exp,i}$ is a moisture from experiment

2.3 Classification of energy consumption

To classify of the energy consumption used fraction from an electrical heater and solar energy. The calculation was done in kilowatt hour (kWh) unit. the solar energy used estimated by Eq.6, which was calculated by the multiplication of an average of solar intensity (*I*, W/m^2) with the area of solar collector (*A*, m^2), and time of solar radiation on the solar collector (*t*, hr.). Also, the electricity used was monitored by using a kilowatt hour meter.

$$\text{SolarEnergy} = A \times t \times I \tag{6}$$

3. Result and discussion

3.1 Solar radiation

Three experiments at the controlled temperature 40, 50, and 60°C, took place on the dates 6-7/12/2012, 29-30/11/2011, 16-17/11/2011, respectively. The solar intensity traces during these times are shown in the Fig.2. The peak of solar radiation intensity occurred during 11.00 a.m.-15.00 p.m., while clouds caused dramatic variations seen in the traces.

3.2 Temperature of rubber sheets

At the beginning, the temperature of rubber sheet was equal the ambient temperature. The surface temperature at the position of T2,T4 and T6 increased due to heat exchanging between rubber sheet and hot air in the cabinet. The variation of temperature at the controlled temperature 40, 50 and 60 °C is shown in the Fig.3.

3.3 Drying kinetics of rubber sheets

In order to compare the drying kinetics of three experiments, the moisture ratios were normalized as shown in the Fig.4. As the air temperature increased, the moisture ratio was rapidly reduced, however the temperatures were limited to below 60 °C in order to avoid burned skin on the rubber sheets. At the beginning of the drying time, in 10 hours of drying, the moisture ratio decreased rapidly as available water evaporated at the surface, but this was later slowed down due to the diffusion of water from inside of the rubber sheet. The seven mathematical models were fit to this drying kinetics. It is found that the modified Henderson and Pabis model gives the best fit with both Midilli and Logarithmic models and also providing high R^2 and low χ^2. The statistical results of models for curve fitting is shown in Table2.

3.4 Energy consumption in the drying process

The fraction of energy consumption shown in the table 3. The input solar energy contributed around 15-32%. It should be noted that this fraction will depend on weather conditions. For an example, the electrical energy consumption of the regulated temperature 50°C was lower than 40 °C, because at the experiment 50°C day, this day was a clear day, but at the experiment 40°C day, it was a cloudy day. This evidence was shown on the left hand side of Fig.2. However, the hybrid system has more advantage than the drying system which used only the electrical heater. The result is shown in Table 3, when compared the total energy consumption between the hybrid system and the electricity only. It was found that the hybrid system can be saved the energy around 10 times of the energy used by the electrical heater only.

4. Conclusion

The drying kinetics of rubber sheets in a hybrid solar-electric system with force convection and regulated air temperature were investigated experimentally. The air temperatures from 40 to 60 °C had a significant effect on drying rate. From the seven of mathematical model test, modified Henderson and Pabis model seemed to best fit these drying data. The fraction of energy consumption of solar energy used was in the range of 15-32%.The dryer hybrid system has more energy saving than the heater dryer which uses only electricity; however the hybrid system has some disadvantages such as it depends on the weather conditions, so it is difficult to control the system.

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Table 1. The mathematical modeling for curve fitting

No	Name of model	Expression of model	References
1	Henderson and Pabis	$MR=exp(-kt)$	[8]
2	Page	$MR=exp(-kt^n)$	[9]
3	Logarithmic	$MR=a\ exp(-kt)+c$	[10]
4	Two-Term Exponential	$MR=a\ exp(-kt)+(1-a)exp(-kat)$	[11]
5	Approximation of Diffusion	$MR=a\ exp(-kt)+(1-a)exp(-kbt)$	[12]
6	Modified Henderson and Pabis	$MR=a\ exp(-kt)+\ bexp(-gt)+C\ exp(-ht)$	[13]
7	Midilli	$MR=a\ exp(-kt^n)+bt$	[14]

Table 2. The statistical results of models for curve fitting

Model	T = 40 ° C			T = 50 ° C			T = 60 ° C		
	R^2	χ^2	constant	R^2	χ^2	constant	R^2	χ^2	constant
Henderson and Pabis	0.9757	0.0016	a=0.9473	0.9746	0.0018	a= 0.9419	0.9768	0.0016	a= 0.9315
			k= 0.1008			k= 0.1260			k= 0.1951
Page	0.9826	0.0011	k=0.1543	0.9781	0.0015	k= 0.1845	0.9850	0.0010	k= 0.2884
			n= 0.8251			n= 0.8359			n= 0.7857
Logarithmic	0.9933	0.0004	a=0.8595	0.9907	0.0006	a= 0.8725	0.9964	0.0002	a= 0.8784
			k= 0.1386			k= 0.1644			k= 0.2483
			c= 0.1222			c= 0.1005			c= 0.0860
Two term Exponential	0.9818	0.0012	a=0.2939	0.9769	0.0016	a= 0.3323	0.9821	0.0012	a= 0.3008
			k= 0.2633			k= 0.2904			k= 0.5015
Approximate Diffusion	0.9931	0.0004	a=0.4696	0.9887	0.0008	a=0.1372	0.9958	0.0003	a=0.1573
			k= 0.0033			k= 0.0099			k= 0.0240
			b= 0.0711			b=18.077			b= 12.1134
Modified Henderson and Pabis	0.9939	0.0004	a= 0.0278	0.9918	0.0006	a= 0.0267	0.9969	0.0002	a= 0.0657
			b= 0.0271			b= 0.0167			b= 0.1288
			c= 0.9211			c= 0.9235			c= 0.7758
			g=-0.0254			g= -0.028			g= 0.0169
			h= 0.1251			h= 0.1499			h= 0.2669
			k=-0.0254			k= -0.0295			k= 0.2654
Midilli	0.9928	0.0004	a=0.9745	0.9921	0.0005	a= 0.9658	0.9927	0.0005	a=0.9745
			b= 0.0038			b= 0.0034			b= 0.0038
			k=-0.1196			k=-0.3797			k=-0.1196
			n=-0.9972			n=-0.3797			n=-0.9972

Table 3. The fraction of energy used in the drying system

Temperature (c°)	Electrical energy(kWh)	Solar energy (kWh)	Fraction of electrical used(%)	Fraction of solar used(%)	Total (kWh)
40	12.55	5.00	71.50	28.50	17.55
50	11.66	5.59	67.58	32.42	17.25
60	20.05	3.80	84.05	15.95	23.85
50(only heater)	288	0	100	0	288

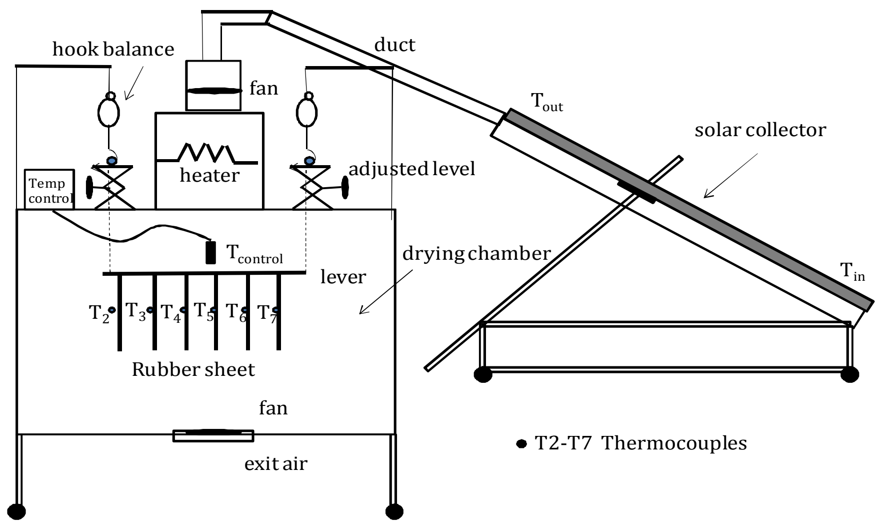

Fig.1. The schematic of solar-electrical dryer

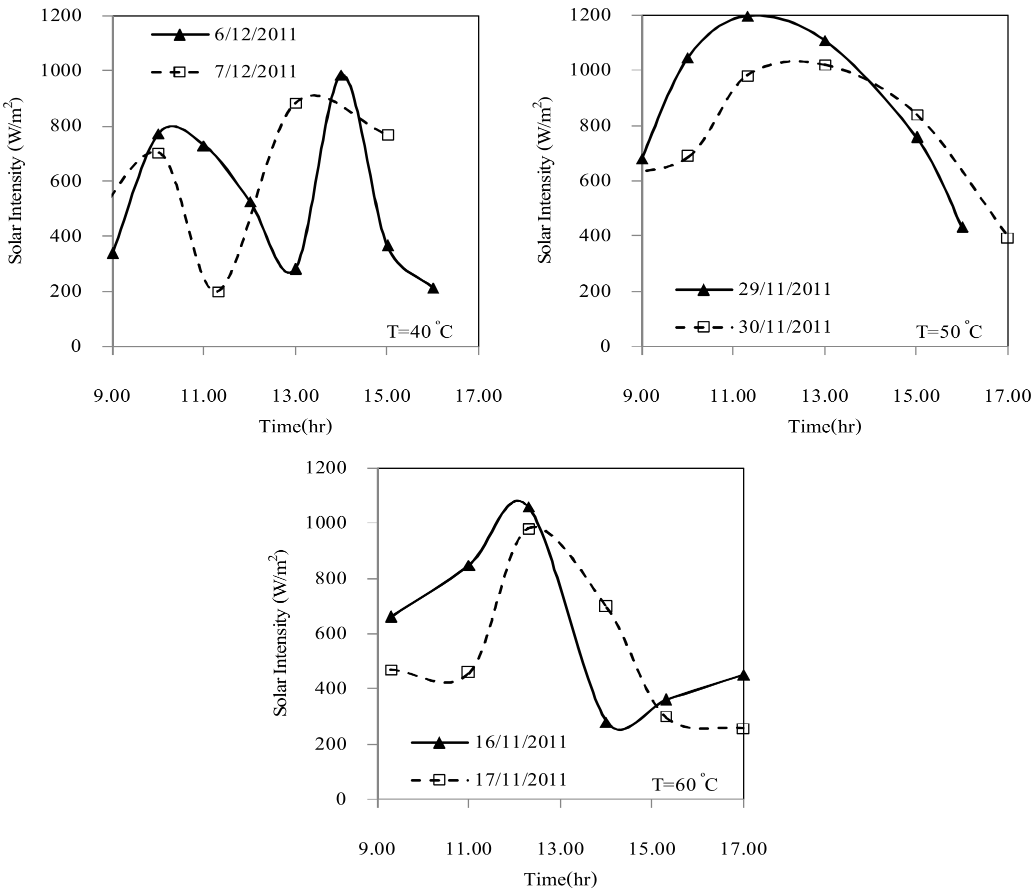

Fig.2. The variation of solar intensity during the drying experimental by dates.

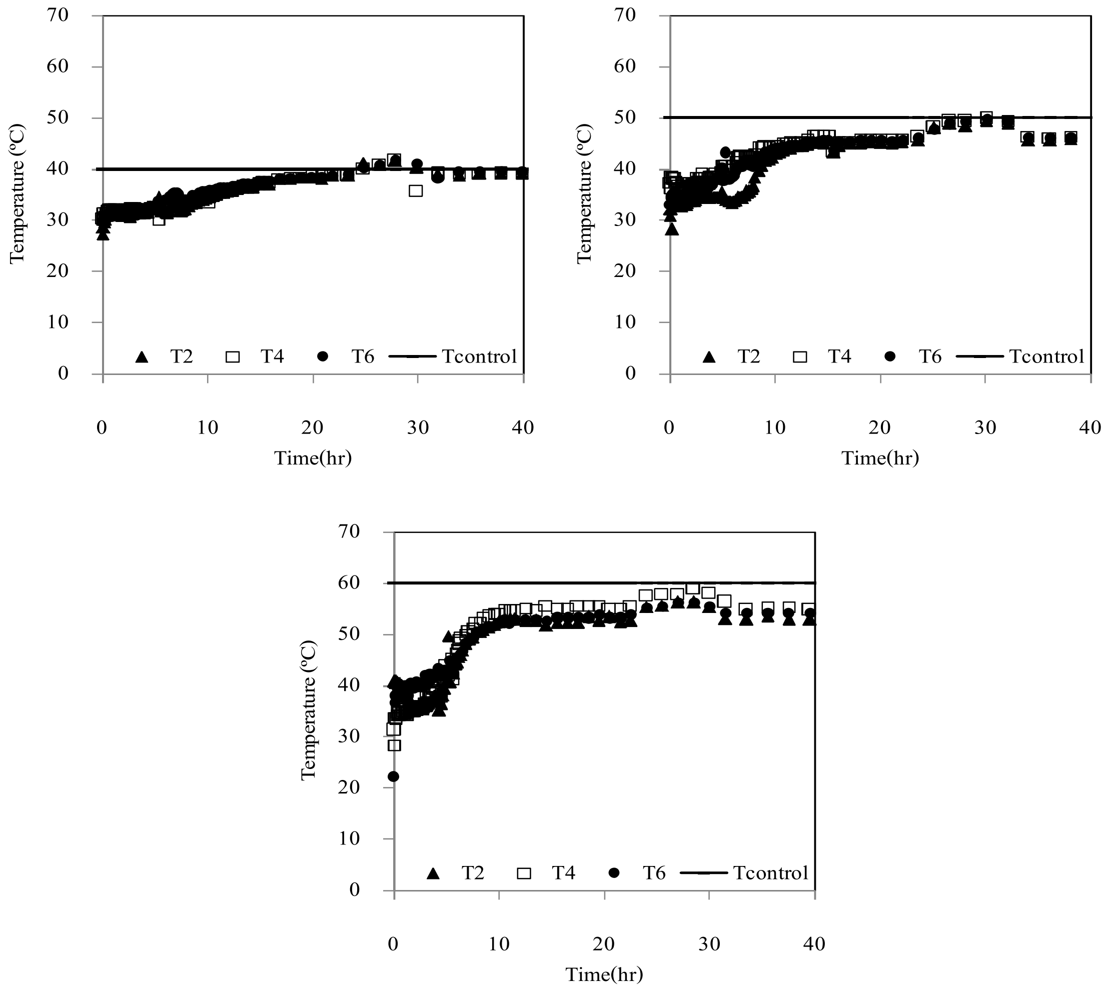

Fig.3. The variation of rubber sheet temperature at the controlled temperature of 40, 50 and 60 ºC.

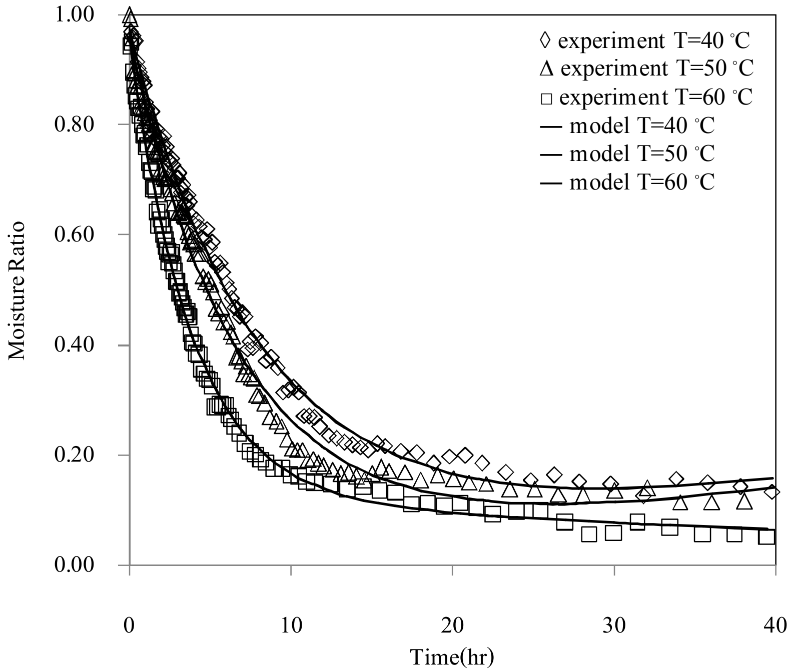

Fig.4. Experimental time traces of moisture ratio at drying air temperature regulated to 40, 50 and 60 °C along with fits by the modified Henderson and Pabis model.