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Mathematical modeling and performance investigation of mixed-mode and indirect solar dryers for natural rubber sheet drying

Racha Dejchanchaiwong [a,b], Auk Arkasuwan [a,c], Anil Kumar [a,c], Perapong Tekasakul [a,c,*]

[a] *Energy Technology Research Center, Faculty of Engineering, Prince of Songkla University, Hat Yai, Songkhla 90112, Thailand*
[b] *Department of Chemical Engineering, Faculty of Engineering, Prince of Songkla University, Hat Yai, Songkhla 90112, Thailand*
[c] *Department of Mechanical Engineering, Faculty of Engineering, Prince of Songkla University, Hat Yai, Songkhla 90112, Thailand*

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ABSTRACT

Smallholder rubber producers typically dry rubber in the open air, a process that takes about seven days, allowing the rubber to deteriorate and thus decreasing the price obtained by the producers. Solar dryers decrease the drying time by 2–3 days, thereby yielding a higher quality product. In this study, performances of mixed-mode and indirect solar drying systems have been investigated for 30 natural rubber sheets. Drying efficiency of the mixed-mode dyer is 15.4% which is higher than the indirect solar dryer (13.3%). The moisture contents of rubber sheets are reduced from 32.3 to 2.0% and 29.4 to 8.0% on a wet basis for mixed-mode and indirect solar drying, respectively, in 4 days. Hii et al. model is the combination of the Page and Two-term drying model. This model is found to best describe the natural rubber sheet drying behavior in both mixed-mode and indirect solar dryers. Coefficient of determination and root mean square error for mixed-mode and indirect solar drying of natural rubber are 0.998 & 0.0096 and 0.996 & 0.0109, respectively. Performance of the mixed-mode dryer is superior to the indirect solar dryer. Therefore, mixed-mode solar dryers are recommended for natural rubber sheet drying to smallholders.

Introduction

Natural rubber latex from the rubber tree (*Hevea brasiliensis*) is made up of an emulsion of rubber particles suspended in the aqueous phase. The aqueous phase, called serum, contains several non-rubber materials such as carbohydrates, proteins, lipids, minerals, microorganisms and water. The rubber particle diameters are range from 0.05 to 5 μm. Freshly, tapped Hevea latex has a pH of 6.5 to 7.1 and density of 0.98 g/cm^3. The total solids of fresh field latex vary typically from 30 to 40% by weight, depending on clone, weather, stimulation, age of the tree, method of tapping, tapping frequency and other factors (Tekasakul et al., 2015).

About 8–10 million tons of natural rubber are produced in the world and Asia is the main source of natural rubber, accounting for around 94%. Thailand is the world leader in export of natural rubber products in international market. Approximately 4 million tons of natural rubber sheet were produced in Thailand in 2014. The three largest natural rubber producing countries (Thailand, Indonesia, and Vietnam) account for 69% of total world rubber production (Madhlopa and Ngwalo, 2007; Tanwanichkul et al., 2013). Natural rubber is the raw material used in the production of automotive tire, shock mounts, seals, couplings, bridge and building bearings, footwear, hoses, conveyor belts, molded products, linings, rolls, gloves, condoms, medical devices, adhesives, carpet backing, thread, foam and other rubber products (Tekasakul and Tekasakul, 2006). It is usually sold in the form of ribbed smoked sheet, dry rubber blocks or concentrated rubber latex.

The safe limit of moisture content in natural rubber is a very important factor for its preservation. It is preserved in the forms of ribbed smoked sheets (RSS), air dried sheets (ADS), block rubber, crepe rubber, and concentrated rubber latex. RSS is one of the leading forms of natural rubber which accounts for about 20% of all products. Smoke houses are used for producing ribbed smoked sheets and smoking is carried from burning of firewood/rubber wood. Construction and maintenance of smokehouse are very expensive for a single small farmer. Hence, these are generally handled by the cooperative or farmer groups in the villages (Breymayer et al., 1993). There are some advanced drying techniques (electromagnetic heater, fluidized bed, heat pump and the vacuum drying) also for natural rubber drying, but these are very energy intensive (Thama et al., 2014).

Alternatively, solar energy is free of charge, environmentally clean, hence, identified as one of the most promising choices among renewable energy recourses (Prakash and Kumar, 2013; Kumar et al., 2014; Shrivastava et al., 2014 and 2015). Smallholders of natural rubber in southern Thailand dry rubber sheet either under the open sun drying or inside shade during rainy season due to shortage of the smokehouse. Solar drying can be either direct or indirect depending on whether the

* Corresponding author at: Energy Technology Research Center, Faculty of Engineering, Prince of Songkla University, Hat Yai, Songkhla 90112, Thailand.
E-mail address: perapong.t@psu.ac.th (P. Tekasakul).

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(a) Mixed-mode solar dryer for natural rubber drying

(b) Indirect solar dryer for natural rubber drying

Fig. 1. Experimental setup of natural rubber sheet drying inside solar dryers.

products are directly exposed to the sunlight. Direct solar dryers receive solar radiation through the transparent walls. On the other hand, indirect dryers require solar collectors to convert the solar radiation to heat and the hot air passing through the collectors is the only medium that dries the products (Phoungchandang and Woods, 2000; Maskan et al., 2002; Kumar and Tiwari, 2006c; Forson et al., 2007; Sreekumar et al., 2008; Maiti et al., 2011). Mixed-mode dryers are the combination of both direct and indirect dryers. Comparison between mixed-mode and indirect-mode of natural convection (passive) solar dryer for maize was studied. Drying cost of the mixed-mode dryer was found lower than others (Simate, 2003).

The moisture content of the raw unsmoked rubber sheet (USS) should not exceed 4% on dry basis before selling to rubber smoking plants or cooperatives. Open sun or inside shade drying of natural rubber sheets are slow routes of drying and it takes about 7 or more days to dry. Further, it leads to quality degradation because of rupture of the polymeric chains and deterioration of natural antioxidants in rubber sheets. These are the reasons to force the smallholder to sell rubber sheet at low price. This financial loss can be recovered by applying user friendly and affordable direct and mixed mode solar drying techniques. Hence, an attempt has been made in design, development and performance testing of direct and mixed-mode solar dryers for natural rubber sheet drying for small farmers.

Literature review of solar drying of natural rubber sheet

Drying is a primary process in natural rubber production. So far, the main challenge is to achieve 99.7–99.8% of dry rubber content (DRC) without sacrifice of its quality. The largest part of the energy consumption is in drying process of natural rubber sheets than any of the other rubber sheet production processes. Firewood consumed is 0.8–1.2 tons for each ton of RSS and about 60 tons of firewood is consumed by every cooperative during the peak months of operation. The requirement of firewood in the smoking process has created many concerns about the scarcity of firewood, price rise and environmental problems (Promtong and Tekasakul, 2007).

Major research in natural rubber sheet drying has been concentrated on controlling the temperature and better airflow distribution inside the smokehouse for uniform drying. Few works are reported on development of solar rubber dryers for smallholders. Solar-assisted smokehouse for the drying of natural rubber on small-scale Indonesian farms has been tested. Results show that there is an enormous prospect in reducing time for smoking and firewood consumption (Breymayer et al., 1993). Tillekeratne et al. (1995) carried out sun drying of natural rubber sheets to study the adverse effects of solar radiation on physical or vulcanization properties of the rubber. The procedure has been formulated for sizing of solar-assisted fixed-bed batch dryers for granulated natural rubber drying. The relation between the heat savings fraction and system parameters has been developed (Pratoto et al., 1997, 1998). Solar drying systems have been fabricated and tested for natural and forced convection drying modes for natural rubber sheets. The drying efficiency has been reported up to 17%. These dryers reduced moisture content from 30 to 2.5% wet basis (% wb) in 5 days without adverse consequence of the raw rubber properties of natural rubber (Siriwardena et al., 2010; Arekornchee et al., 2014; Janjai et al., 2015). Even though the results of these investigations have shown plenty potential of solar energy

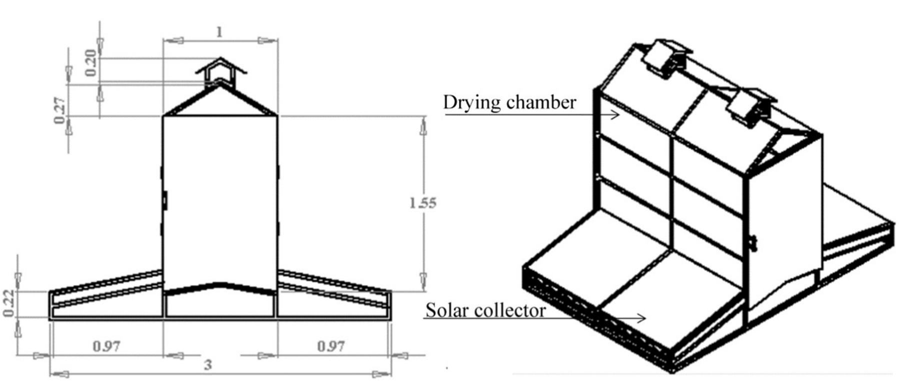

Fig. 2. Schematic diagram of solar dryer.

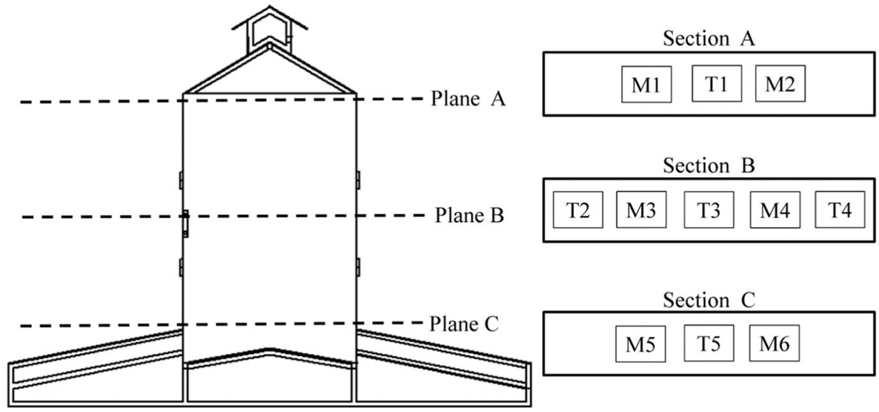

Fig. 3. Locations of planes A, B and C in chamber and positions of temperature and mass of sample rubber measurement.

utilization in rubber drying. But, so far, solar dryers have not been adopted commercially.

Mathematical modeling of designed drying system is necessary to justify its functionality. Further, it can be used in prediction of moisture evaporation rate and specific energy consumption of the drying system (Siriwardena and Fuller, 1997; Tirawanichakul et al., 2011; Shrivastava et al., 2015). Tanwanichkul et al. (2013) developed a mathematical model to predict the temperatures of drying chamber, rubber sheets and ground floor for a sandwich greenhouse dryer. The moisture content of the rubber sheets was reduced from 36.4% db to 2.8% db in lesser than 2 days in this dryer. Recently, drying kinetic models were used for analyzing the drying behavior of rubber sheet drying for different drying conditions such as hybrid solar-electric, vacuum drying and greenhouse drying. Modified Henderson and Pabis model was found the best drying kinetic model for rubber sheet drying in hybrid solar-electric Dryer with force convection mode (Werapun et al., 2014).

A limited number of research was conducted on mixed-mode and indirect solar drying of natural rubber sheets despite the massive potential of solar energy. Therefore, the main objectives of this research are: (i) design and development of mixed-mode and indirect solar rubber dryers for smallholders (ii) mathematical modeling to describe the drying behavior of rubber sheets and (iii) investigates the performance of the fabricated drying systems.

Method

Experimental setup

Mixed-mode and indirect solar dryers are installed at Energy Technology Research Center in Prince of Songkla University, Thailand (07°01′N 100°27′E). Experimental setups of mixed-mode and indirect solar drying for natural rubber sheet are shown in Fig. 1.

The complete drying system has two parts: drying chamber and solar air heating collectors. Dimensions of the drying chamber and solar collectors are 1.0 m × 2.0 m × 1.55 m and 1 m × 2 m, respectively, as shown in Fig. 2.

Instrumentation

Mass of rubber sheets was weighed at six positions (M1, M2, M3, M4, M5 and M6), as shown in Fig. 3, at every hour by a balance (SHIMADZU, ELB 3000). The solar radiation was measured at the solar collector surface (position P) by a pyranometer (KIPP & ZONEN, CM 3). Type-K thermocouples were used to measure temperatures at five positions in the drying chamber (T1, T2, T3, T4 and T5); four positions of the solar collector exits (T6, T7, T8 and T9); two positions of the chimney (T10 and T11); and one position for ambient air (T12) as shown in Fig. 3. Global solar radiation and temperature were recorded by the data logger (DataTaker, DT605 series 3). Air velocity was measured at four positions (V1, V2, V3 and V4) by the anemometer (Testo, 405-V1). Relative humidity (RH) was measured at three positions (RH1, RH2 and RH3) by a humidity meter (Testo), as shown in Fig. 4. The moisture content was determined by ASAE methods in the laboratory.

Sample preparation

Manufacturing process of rubber sheets is started from latex. The fresh latex containing about 35–40% of dry rubber content (DRC) was collected from farmers (Step 1). It was diluted with water to achieve the DRC of about 15–18% and 2% wt./vol. of formic acid was added to coagulate in the coagulation tanks (Step 2). These tank have channels for separators to give the thick slabs of the rubber sheets. The mixture was stirred to mix well and all bubbles were removed by surface wiping (Step 3). These bubbles may cause quality degradation of the rubber sheets. Then separators were inserted in the channels and left to form lumps of coagulum for 3–4 h (Step 4). The hardened rubber slabs with moisture content of about 60% were then removed from the coagulation tank, and squeezed to form thin rubber sheets (Step 5). The thickness of rubber sheets (3–4 mm) was controlled with the constant spacing of milling and it was cross checked with a vernier caliper after regular interval of time. Finally, the rubber sheets were placed in the mixed-mode and indirect solar dryer for drying (Step 6–7). The complete manufacturing process of air dried rubber sheets is shown in Fig. 5. Steps 1 to 5 in Fig. 5 were carried out at Saikao Cooperative, located in the Muang district, Songkhla province, Thailand and step 6–7 at Prince of Songkla, Hat Yai district, Songkhla province, Thailand.

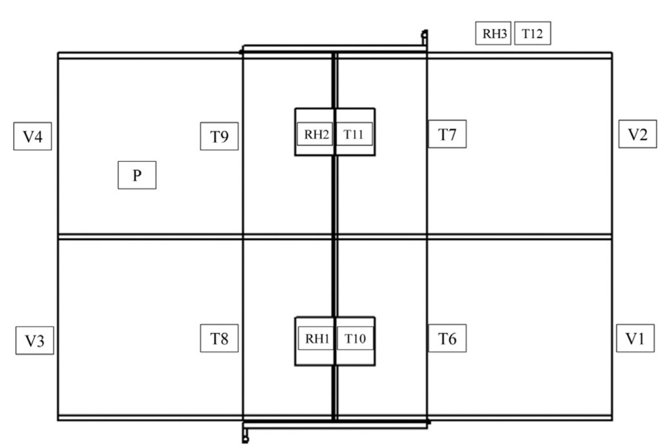

Fig. 4. Positions of temperature, velocity and relative humidity measurement.

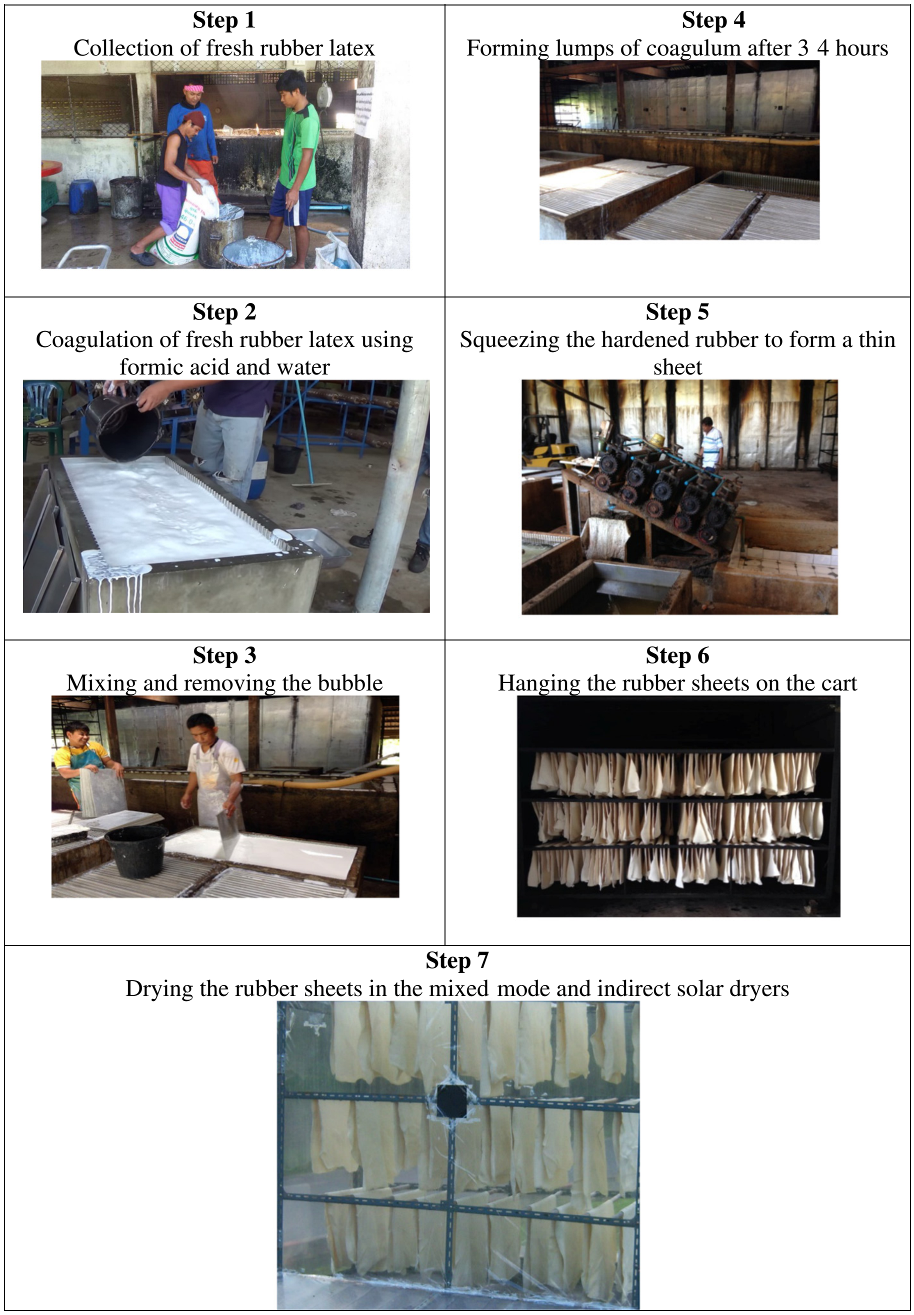

Fig. 5. Manufacturing process of natural rubber sheets.

Experimentation

Natural rubber sheet drying experiments were conducted in designed and fabricated solar drying systems during October 2008 to January 2009 from 09:00 to 18:00 h. Drying chamber has even spanned roof structure, made from polycarbonate sheets and concrete floor. Two sets of experiments were conducted separately for mixed-mode and indirect solar drying. Solar radiations were coming through the roof and sidewalls of drying chamber of the mixed mode solar dryer. These were utilized directly in heating air and natural rubber sheets inside the chamber. At the same time, hot air was also coming from the bottom of mixed-mode solar dryer through the solar air heating collectors. Whereas in indirect solar dryer, walls and roof of drying chamber made opaque and painted black to absorb solar radiation to from heat. Heat from the walls was transferred to the chamber via conduction. Each set of experiments was performed for 4 days with 30 numbers of rubber sheets (50 cm × 90 cm × 0.4 cm). Global solar radiation, mass of the rubber sheet, temperature & humidity inside and outside the dryer, inlet & outlet velocity of supply air and other ambient parameters were recorded at regular intervals of time.

Numerical computation

Mathematical modeling

The initial dry and wet basis moisture contents of sample rubber are usually about 40–50% db and 28.6–33.3% wb, and the final moisture content should be nearly 4% db and 3.8% wb, respectively. Wet and dry basis moisture contents are most commonly used expressions to

Table 1
Mathematical models for rubber sheet drying.

Model no.	Name of model	Equation	References
1	Page	$MR = \exp(-kt^n)$	Zhang and Litchfield (1991)
2	Modified Page	$MR = \exp(-(kt)^n)$	Overhults et al. (1973)
3	Verma et al.	$MR = a\exp(-kt) + (1-a)\exp(-gt)$	Verma et al. (1985)
4	Henderson and Pabis	$MR = a\exp(-kt)$	Zhang and Litchfield (1991)
5	Modified Henderson and Pabis	$MR = a\exp(-kt) + b\exp(-gt) + c\exp(-ht)$	Karathanos (1999)
6	Two term	$MR = a\exp(-k_1t) + b\exp(-k_2t)$	Henderson (1974)
7	Weibull distribution	$MR = a - b\exp(-(kt^n))$	Stamatios et al. (2006)
8	Logarithmic	$MR = a\exp(-kt) + c$	Togrul and Pehlivan (2003)
9	Hii et al.	$MR = a\exp(-kt^n) + b\exp(-gt^n)$	Hii et al. (2009)
10.	Diffusion approach	$MR = a\exp(-kt) + (1-a)\exp(-kbt)$	Demir et al. (2007)

where t is the drying time (h), and a, b, c, g, h, k, k_1, k_2, and n are the constant value.

describe the water content of agricultural materials (Prakash and Kumar, 2014).

Dry basis moisture content (M_d) is described by the percentage corresponding to the ratio of the weight of water (W_w) and weight of the dried mass (W_d), as follows:

$$\%M_d = \frac{W_w}{W_d} \times 100 \tag{1}$$

In wet basis, the moisture content (M_w) is described by the percentage corresponding to the ratio of the weight of water (W_w) and total weight of the rubber sheet (W_t), as follows:

$$\%M_w = \frac{W_w}{W_t} \times 100 \tag{2}$$

The moisture ratio (MR) of rubber sheet during drying experiments can be calculated by:

$$MR = \frac{(M_t - M_e)}{(M_o - M_e)} \tag{3}$$

where M_t is the total moisture content at any drying time (% wb), M_o is the initial moisture content (% wb), $M_e$is the equilibrium moisture content (% wb).

Equilibrium moisture content (EMC) is the most essential parameter of the drying material, especially in a tropical country where relative humidity is high. EMC of natural rubber sheet was evaluated in the range of 30–60 °C temperature and 0–100% RH. Halsey equation is the best fitting of EMC of rubber sheet (Tirawanichakul et al., 2007):

$$RH = \exp\left(\frac{-11.08492}{RT_{abs}} \times M_e^{-0.886330}\right) \tag{4}$$

where RH is the relative humidity (decimal), R is the universal gas constant (8.314 kJ/kmol-K), T_{abs} is the absolute temperature (K), and M_e is the equilibrium moisture content (decimal, db).

Mathematical models of thin layer drying were used to describe the drying behavior of rubber sheet drying. The equations express the moisture ratio as a function of drying time. These empirical models and semi-theoretical models were developed from experimental results using the statistical nonlinear regressions. The best fitting empirical models for rubber sheet drying under different drying conditions are shown in Table 1.

The coefficient of determination (R^2), and root-mean-square error (RMSE) were applied to determine the best mathematical drying model for rubber sheet drying under mixed mode and indirect solar drying as:

$$R^2 = 1 - \frac{\sum_{i=1}^{n} (M_{p,i} - M_{ex,i})^2}{\sum_{i=1}^{n} (M_{ex,i})^2} \tag{4}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} (M_{p,i} - M_{ex,i})^2}{N}} \tag{5}$$

where $M_{ex,i}$ is the experimental value, $M_{p,i}$ is the predicted value, and N is the number of observations.

Performance indicator

The most common indicator for dryer performance is thermal efficiency. It is defined as:

$$\eta_{solar\ \ dryer} = \frac{m_L L}{IA_t} \tag{6}$$

where, $\eta_{solar\ \ dryer}$ is the thermal efficiency of the solar rubber sheet dryer, m_L is the mass of removed water (kg), L is the latent heat of vaporization (kJ/kg), I is the total solar insolation (kJ/m^2), and A_t is the total area exposed to solar radiation (m^2).

In the present study, both dryers used solar collectors as a source of indirect heat. Therefore, it is important to know the efficiency of the

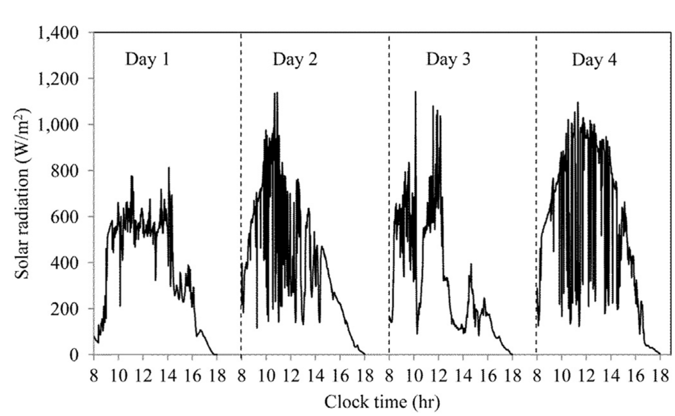

Fig. 6. Variation of solar radiation during mixed-mode solar drying.

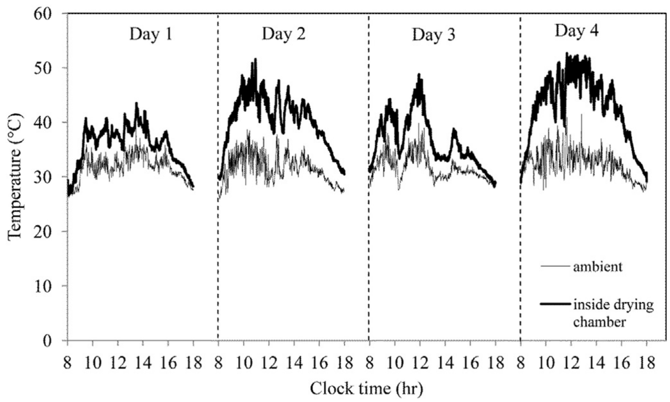

Fig. 7. Variation of drying chamber and ambient temperature during mixed-mode solar rubber sheet drying.

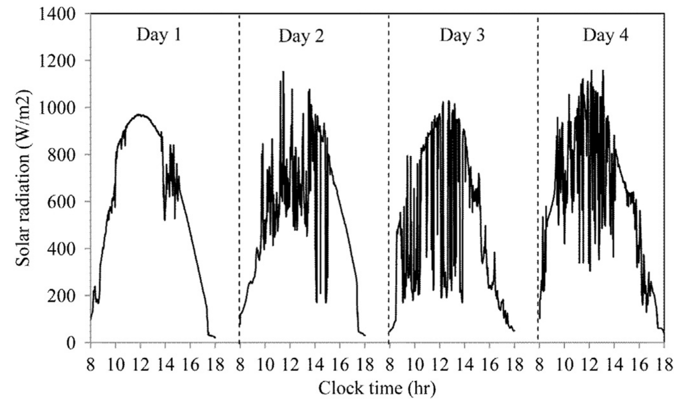

Fig. 9. Variation of solar radiation during indirect solar drying.

collectors under operating conditions. The solar collector efficiency ($\eta_{solar\ \ collector}$) can be calculated as:

$$\eta_{solar\ \ collector} = \frac{Q}{IA_s} \tag{7}$$

where Q is the thermal energy transfer from the solar collector to air (kJ) that can be estimated from

$$Q = m_a c_p (T_i - T_o) \tag{8}$$

where, m_a is the mass of inlet air (kg), c_p is the air specific heat (kJ/kg°C), T_i is the inlet air temperature in solar collector (°C), T_o is the outlet air temperature in solar collector (°C).

Mass of air at solar collector is given as

$$m_a = \rho \times V \times A_c \times t \tag{9}$$

where A_c is the cross-sectional area of inlet solar collector (m^2), ρ is the density of air (kg/m^2), V is the average air velocity at the solar collector inlet (m/s), and t is the time (s).

Results and discussion

Experimental investigation

Experimental investigation of natural rubber sheet drying inside mixed-mode solar dryer

In the mixed-mode solar drying, solar energy was being utilized by two ways, i.e. (i) indirect heating — the ambient air passing through the solar air heating collector, getting heated and supplied to the drying chamber (ii) direct heating — solar radiation through the transparent walls and roof of the drying chamber.

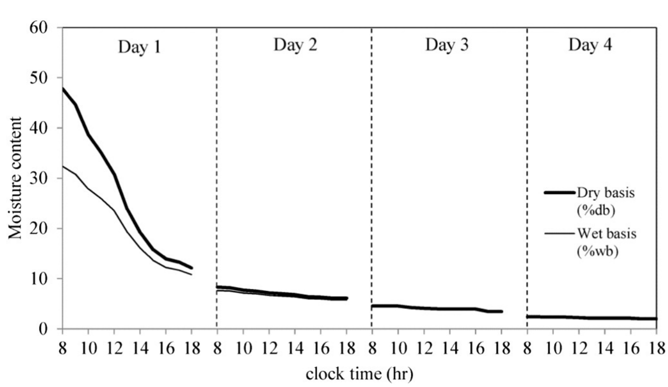

Fig. 8. Moisture content of natural rubber sheet during mixed-mode solar drying.

First set of experiment for mixed-mode solar rubber sheet drying was conducted during the 28th–31st October from 08:00 h to 18:00 h. The weather conditions on the 1st and 3rd days were partially cloudy and hazy. The solar radiations and temperatures are gradually increased with time of the day and their peak values are between 10:00 and 12:00 h. The average values of solar radiations for all four days are 379.9 W/m^2, 402.6 W/m^2, 319.3 W/m^2, and 528.6 W/m^2, respectively as shown in Fig. 6. Total solar radiation energy is received in all four consecutive days were 136.8 MJ, 144.72 MJ, 114.9 MJ, and 190.3 MJ.

The hourly chamber temperatures are plotted with respect to clock time and compared with ambient temperature as shown in Fig. 7 The average drying chamber temperature in all four days were recorded as 36.5 °C, 40.5 °C, 36.5 °C, and 43.6 °C, respectively. The overall average temperature of drying chamber is 39.2 °C. There is a significant temperature difference (7.2 °C) between drying chamber and ambient temperature. This higher temperature is maintained due to the greenhouse effect.

Dry and wet basis moisture contents (MC) of 30 sheets are shown in Fig. 8. In the first day, the moisture content was decreased from 47.8% to 13.3% and 32.3% to 11.8% for dry and wet basis, respectively. Constant-rate drying period is observed during first six hours and the rest of drying is in the falling-rate period. MC for dry and wet basis was decreased from 13.3 to 2.1% and 11.8 to 2.0%, respectively, in next three consecutive drying days. There is not much difference in the value MC on dry and wet basis in rest of drying days. This is because the moisture in the rubber sheets on days 2–4 is small. Drying rate is highest on the 1st day due to high moisture content in the product. On the other hand, open sun drying needs more than 10 days for drying in the same weather conditions (Tekasakul, 2011). Hence, mixed-mode solar dryer is reduced drying time significantly for natural rubber sheets.

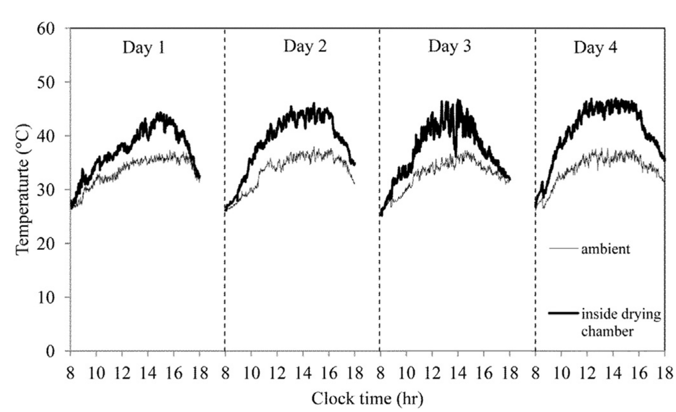

Fig. 10. Variation of drying chamber and ambient temperature during indirect solar drying.

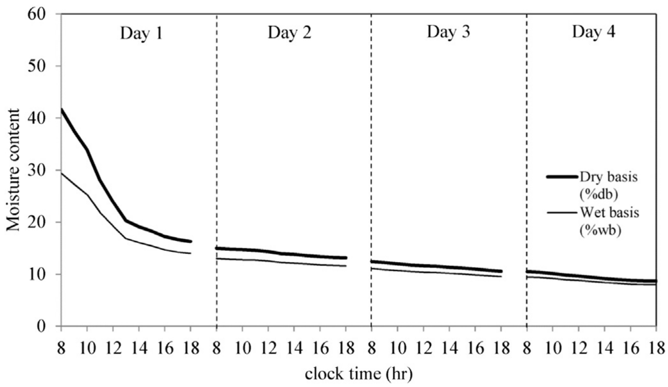

Fig. 11. Moisture content of natural rubber sheet during indirect solar drying.

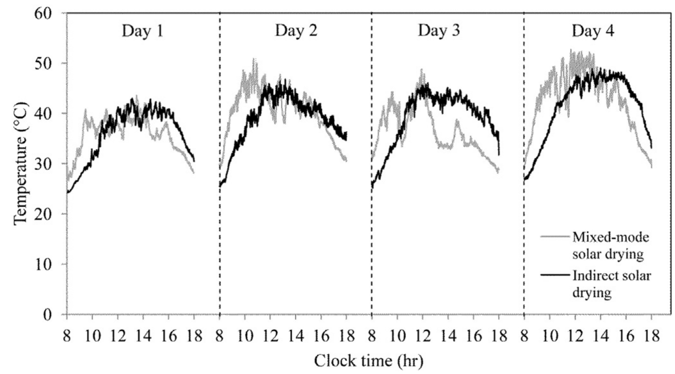

Fig. 13. Variation of temperature inside drying chamber during mixed-mode and indirect solar drying.

Experimental investigation of natural rubber sheet drying inside indirect solar dryer

The first set of natural rubber sheet drying experiment inside indirect solar dryer was carried out from 8th–11th January. There were almost similar weather conditions as mixed mode drying. The average solar radiations on days 1–2–3–4 are 570.0 W/m^2, 533.7 W/m^2, 462.5 W/m^2, and 597.9 W/m^2, respectively (Fig. 9). Total solar energy received for drying were 133.9 MJ, 115.3 MJ, 99.9 MJ, and 129.3 MJ for subsequent days of drying. In the indirect solar drying, solar collectors were to convert the solar energy into useful heat and the solar radiation on the side walls and roofs was conducted through the chamber. The collector made of black zinc plate was used to absorb the solar energy before releasing to the air entering collector due to buoyancy.

The average temperature rise inside drying chamber is 6 °C as compared to ambient temperature as shown Fig. 10. Average drying chamber temperatures on experimental days 1–2–3–4 were 38.3 °C, 39.0 °C, 37.3 °C, and 40.8 °C, respectively. The overall average drying chamber temperature is 38.9 °C. The maximum temperature was 49 °C at 14:00 h on the fourth day as less relative humidity inside the drying chamber.

Wet and dry basis moisture contents of natural rubber sheets with respect time of each day are shown in Fig. 11. On the first day, the moisture content was decreased from 41.7% to 16.7% and 29.4% to 14.3% for dry and wet basis, respectively. Constant-rate drying period lasted about 5 h. MC for dry and wet basis was decreased from 16.7% to 8.7% and 14.3% to 8.0%, respectively in next three consecutive drying days. In this case, there is rather a difference in the value of MC on dry and wet basis in rest of drying days. It is because the drying rate was slower causing greater different between the values of weight of the dry rubber sheet and total weight in days 2–4.

Comparison between mixed-mode and indirect solar drying of natural rubber sheet

Performance of mixed-mode and indirect solar dyer has been compared in Figs. 12–14. The solar radiation during the mixed-mode solar drying experiment was lower than indirect solar drying due to partial cloudy condition as shown in Fig. 12. But total solar energy received was 586.72 MJ and 464.3 MJ for mixed-mode and indirect solar drying, respectively. This is because the mixed-mode solar dryer has received more solar energy than indirect solar drying. Average drying chamber temperatures were also observed higher in case of mixed-mode solar drying of natural rubber which is desirable for drying as shown in Fig. 13. On the fourth day of drying, the sky was clear, therefore clear differences in temperature can be seen in the same figure.

The hourly moisture contents on a wet basis for all four days of experiments in both modes of drying are given in Fig. 14. In the beginning, drying rate was significantly higher in both cases. There was remarkable faster rate of moisture removal in mixed-mode solar drying of a natural rubber sheet due to maximum utilization of solar energy. Drying was faster in the first day of drying as it depends on moisture content in both cases of solar drying. The moisture content of sheets was rapidly decreasing to 11.8% wb and 14.3% wb for mixed-mode and indirect solar drying, respectivly in 1st day of drying i.e. 63.5% and 51.4% of total moisture removal in these cases. The moisture contents of natural rubber sheets were decreased from 32.3% wb to 2.0% wb and 29.4% wb to 8.0% wb by mixed-mode and indirect solar drying, respectively, in four days. Total 93.8% and 72.8% of initial moisture were removed after 4 days for mixed-mode and indirect solar drying, respectively. Based on the above experimental investigation, It can be concluded that the mixed-mode solar dryer performed much better than the indirect solar drying of the natural rubber sheet.

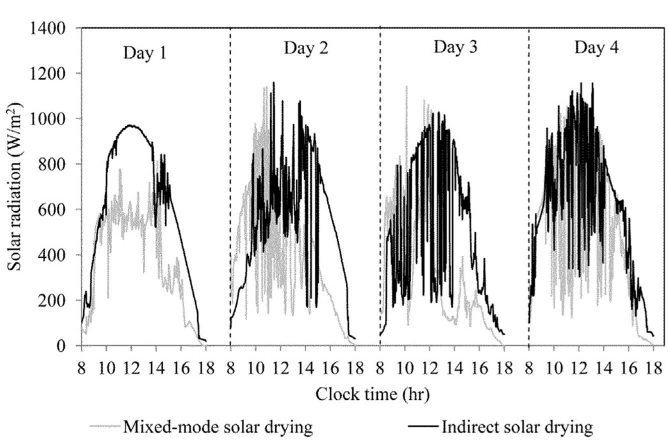

Fig. 12. Variation of solar radiation during mixed-mode and indirect solar drying.

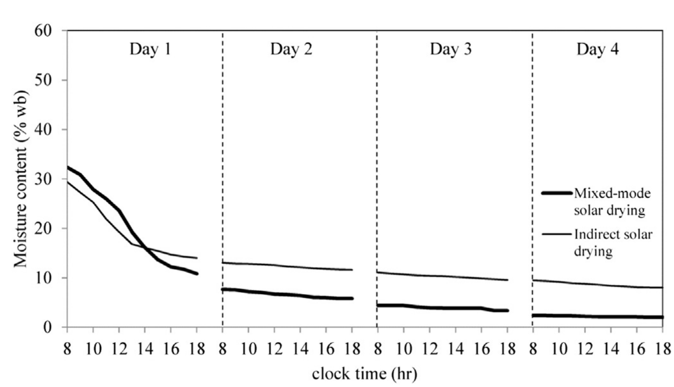

Fig. 14. Moisture content during mixed-mode and indirect solar drying.

Arekornchee et al. (2014) conducted rubber sheet drying experimentations under open sun, natural and forced convection modes in greenhouse drying. Initial moisture content of natural rubber sheet was 30% wb. It was reduced up to 7.0%, 4.0% and 2.5% for open sun, natural and forced convection modes, respectively, in 5 days. In the present study, the moisture content was reduced up to 2.0% wb in 4 days for the case of mixed-mode solar drying. Drying time can be saved in the present research. Hence, designed mixed-mode solar dryer performed much better than the earlier developed solar dryers.

Equilibrium moisture content of natural rubber sheet during mixed mode and indirect solar dryring

Equilibrium moisture content (EMC) of rubber sheet is evaluated from Eq. 4. Relative humidity and temperature are main governing parameters in this equation. RH and temperature were in the range of 31.5–91.2% and 28.2–50.5 °C for mixed-mode solar drying and, 24.3–84.3% and 24.2–49.0 °C for indirect solar drying, respectively (Figs. 15a and 16a). EMC of natural rubber sheet were 0.14–2.26% wb and 0.14–1.65% wb for mixed-mode solar drying and indirect solar drying, respectively, as shown in Figs. 15b and 16b. The values of M_e is significant in comparison with M_t and $M_o$as clearly depicted from these figures. Therefore, M_e cannot be negligible for rubber drying in Eq. 3.

Mathematical modeling of mixed-mode and indirect solar drying of natural rubber sheet

Results of the regression analyses performed on the experimental data are given in Table 2. The highest values of R^2 and the lowest RMSE values represent the best fitting ability of the mathematical model for drying. R^2 and RMSE values were calculated in the range of 0.905–0.998 & 0.0096–0.0780 for mixed-mode and 0.925–0.996 & 0.0109–0.0463 for indirect solar drying. Hii et al. model was found to

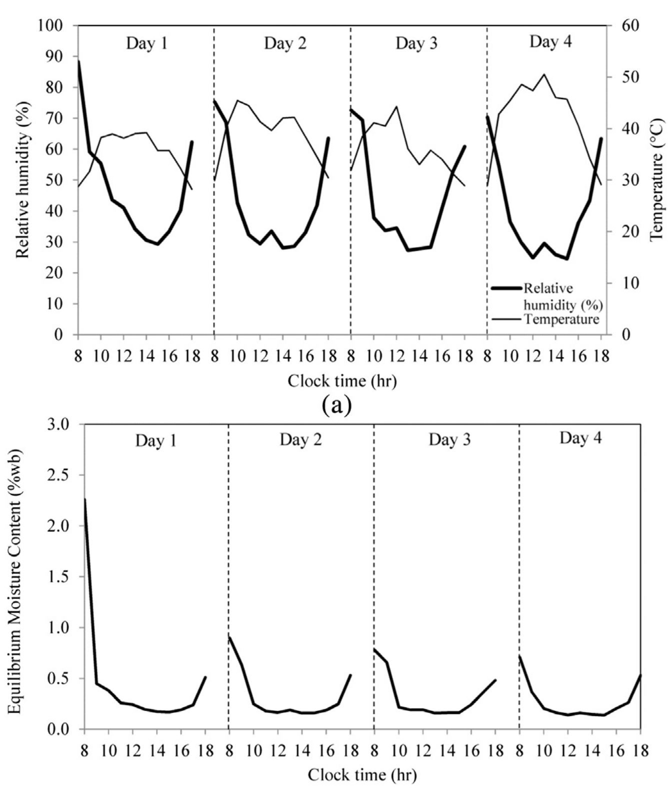

Fig. 15. (a) RH and temperature and (b) EMC of natural rubber sheet during mixed-mode solar drying.

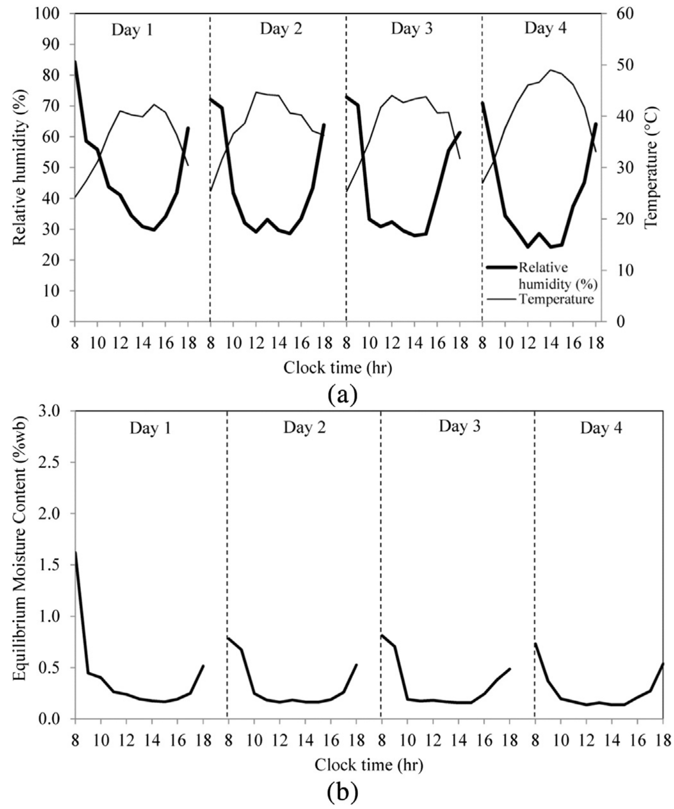

Fig. 16. (a) RH and temperature and (b) EMC of natural rubber sheet during indirect solar drying.

Table 2
Results of non-linear regression analyses for rubber sheet drying curve fitting.

Name of model	Mixed-mode solar drying			Indirect solar drying		
	Constant coefficients	R^2	RMSE	Constant coefficients	R^2	RMSE
Page	k = 0.034 n = 0.637	0.961	0.050	k = 0.256 n = 0.366	0.934	0.0434
Modified page	k = 0.074 n = 0.637	0.961	0.050	k = 0.024 n = 0.367	0.934	0.0434
Verma et al.	k = 0.170 a = 0.682 g = 0.020	0.984	0.0324	k = 0.007 a = 0.490 g = 0.267	0.986	0.0202
Henderson and Pabis	k = 0.053 a = 0.848	0.905	0.0780	k = 0.001 a = 0.693	0.941	0.0863
Modified Henderson and Pabis	k = 0.020 a = 0.164 g = 0.020 b = 0.164 c = 0.749 h = 0.194	0.988	0.0284	k = 0.291 a = 0.553 g = 0.007 b = 0.246 c = 0.246 h = 0.007	0.988	0.0183
Two term	k_1 = 0.020 a = 0.327 k_2 = 0.194 b = 0.749	0.987	0.0284	k_1 = 0.291 a = 0.553 k_2 = 0.007 b = 0.493	0.988	0.0181
Weibull distribution	k = 0.199 n = 0.739 a = 0.077 b = −0.995	0.972	0.0423	k = 0.327 n = 0.532 a = 0.279 b = −0.763	0.950	0.0382
Logarithmic	k = 0.124 a = 0.920 c = 0.109	0.965	0.0472	k = 0.178 a = 0.668 c = 0.345	0.925	0.0463
Hii et al.	**k = 0.001** **n = 1.694** **a = 0.265** **b = 0.729** **g = 0.051**	**0.998**	**0.0096**	**k = 0.001** **n = 1.448** **a = 0.466** **b = 0.538** **g = 0.136**	**0.996**	**0.0109**
Diffusion approach	k = 0.170 a = 0.682 b = 0.117	0.984	0.0324	k = 0.267 a = 0.509 b = 0.025	0.986	0.0202

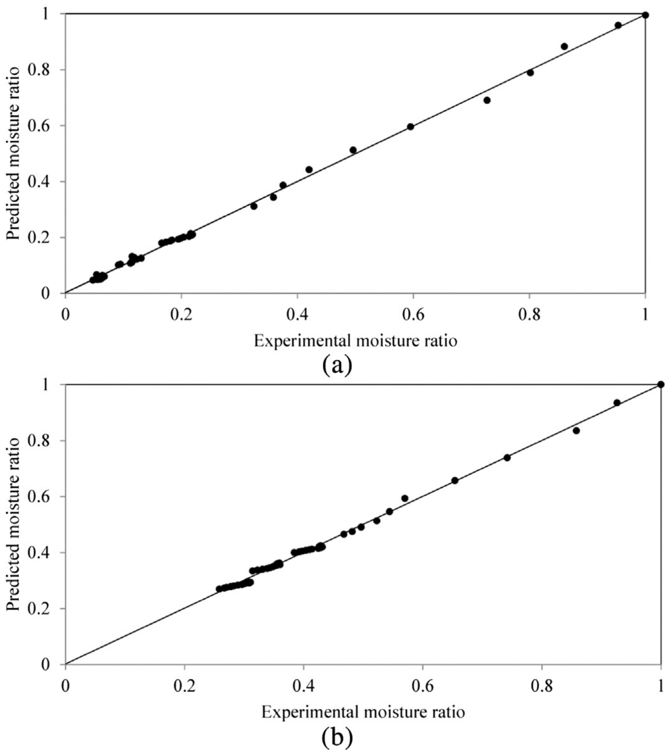

Fig. 17. Predicted vs experimental moisture ratio. (a) Mixed-mode solar drying, and (b) indirect solar drying.

be the best model for fitting the thin layer rubber sheet drying characteristics with a highest R^2 of 0.998 and 0.996 and lowest RMSE of 0.0096 and 0.0105 for mixed-mode and indirect solar drying. The predicted and experimental values of moisture ratio for mixed-mode solar drying and indirect solar drying are shown in Fig. 17. The data points lie around the 45° straight line. Therefore, Hii et al. model is suitable to describe the drying behavior of natural rubber sheet in a given conditions.

Performance analysis of mixed-mode and indirect solar drying of rubber sheet

The efficiency of solar collector is calculated and given in Table 3. It is found in the range of 19.6–22.8% and 19.9–21.5% for mixed-mode and indirect solar rubber sheet drying, respectively. There is no significant difference in the collector efficiency under these drying modes. This shows the consistency in recording experimental data. However, minor difference in efficiency is due to shadow of opaque envelope on the collector during the experiment.

The overall conversion efficiency of the mixed-mode and indirect solar dryer were determined in the range of 0.4–15.4% and 1.3–13.3%, respectively, and given in Table 4. The drying efficiency of both dryers was high during the first day and thereafter, it is gradually decreasing for subsequent days of drying. Maximum utilization of solar energy occurred on the first day of drying because the efficiency of moisture removal decreases as the moisture content decreases. Therefore, utmost conversion efficiency takes place during the first day of drying and it is deceased with successive drying days.

The maximum conversion efficiencies of mixed-mode and indirect solar dryer are 15.4% and 13.3%. These are on the higher side of the expected drying efficiency of natural convection solar dryers which lies between 10 and 15% (Anon, 1997) and close to results obtained by Siriwardena et al., 2010. On the other hand, indirect solar dryer is slightly better in term of quality as sheets are not directly exposed to the sun.

Table 3
Efficiency of solar collector.

Type drying experiments/#	Efficiency of solar collector (%)			
	Experiment 1st day	Experiment 2nd day	Experiment 3rd day	Experiment 4th day
Mixed-mode solar rubber sheet dryer	22.6	22.8	19.6	22.4
Indirect solar rubber sheet dryer	20.6	19.9	20.78	21.5

Table 4
Efficiency of mixed-mode and indirect solar dryer for rubber sheet drying.

Type drying experiments.	Efficiency of solar rubber sheet dryer (%)			
	Experiment 1st day	Experiment 2nd day	Experiment 3rd day	Experiment 4th day
Mixed-mode solar rubber sheet dryer	15.4	1.8	0.6	0.4
Indirect solar rubber sheet dryer	13.3	2.1	1.6	1.3

Conclusion

The mixed-mode and indirect solar dryer are designed and experimentally investigated for rubber sheet drying. Following conclusions have been drawn from the present study:

I. The moisture content of the sheets is reduced from 32.3 to 2.0% wb and 29.4 to 8.0% wb for mixed-mode and indirect solar drying respectively in less than 4 days.
II. The Hii et al. model is found best to describe the solar drying behavior of rubber sheets for mixed-mode and indirect solar drying based on R^2 (0.996–0.998) and RMSE (0.0096–0.0109) values.
III. The maximum efficiency of the mixed-mode and indirect solar dryer are 15.4% and 13.3% respectively.
IV. Mixed-mode solar dryer is superior to the previously developed solar dryers for natural rubber sheet drying in terms of moisture removal rate and drying time. Drying time is reduced from 7 days to 4 days.
V. The dried sheets have a superior look in terms of color and cleanliness than those from open air drying.
VI. Other benefits include the ease of operation, no skilled manpower required for monitoring, no use of biomass, and environmental friendly process.
VII. Some heat losses were observed from the walls of the indirect solar dryer. Thus walls can be coated with an insulator to enhance the efficiency of the system.

Therefore, the mixed-mode solar dryer performs better than indirect solar dryer in given ambient conditions.

Acknowledgments

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