Experiment and Simulation Studies of Drying Kinetics for A Natural Rubber Sheet by Hot-Air Drying with Difference Heat Sources

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Abstract

This study is investigated model for describing drying kinetics of the natural rubber sheet using hot air drying but it is different in heat sources. The first heat source comes from the combustion of charcoal briquette by coconut shell (biomass) and another heat source comes from the combustion of liquid petroleum gas (LPG). The controlled temperature, 40, 50 and 60°C of hot air is sent to the drying chamber, where the five rubber sheets located with the range of the initial moisture from 64.77% to 86.46% dry basis. Then the experimental results are fitted by non-linear regression analysis, to find the important parameter of drying kinetic process, named the effective diffusion coefficient. Moreover, this parameter is obtained as the input parameter to the 2-D FEM simulations, which are the governing equations of heat conduction and mass transport to validate the experimental results. The simulation results yields to predict the tendency of the experimental results for both moisture ratio and temperature.

Keywords: drying kinetic model, rubber sheet drying, and heat source from biomass.

1. Introduction

Thailand is one of the country in the world, where produces a natural rubber. Approximately, the latex produced around the world, 35% of it comes from Thailand, so Thai rubber industrial has the influence on economic and social of Thailand because of its production value. [1] Generally, the natural rubber has produced in four types; Ribbed smoked sheet, STR20, concentrated latex and other. Normally, agriculturist uses sunlight for drying natural rubber. This is a conventional method which can be used only daytime and depends on the weather condition; moreover, there is a risk of deterioration. In order to avoid these problems, a solar dryer with biomass back-up heater is proposed by Ref.[2]. In Ref. [3], they developed dryer for rubber sheet drying by using sunlight, hot-air. The final moisture content was in the range of 1.5% at the temperature 45-55 °C. The importance parameter for drying process is an equilibrium moisture content. Thus, many researcher tried to develop mathematical models for describe the difference drying methods, such as Jeentada W. et al. [4], compared 12 mathematical models for determine equilibrium moisture content at the temperature control 40-70 °C. Suchonpanit W. et al [5], determined the equilibrium moisture content by varying drying time of rubber sheet at green house drying, hot air drying, and infrared drying

The objective of this work aims to study drying kinetics for determine the important parameter named moisture diffusion coefficient of drying process with different heat sources (LPG and biomass) then this parameter is used in the simulation study section.

2. Materials and Methods

2.1 Materials and Drying Equipments

In order to study drying kinetics, the rubber sheets were cut as a small square shape pieces which dimension of 2x2 cm^2 for investigate the initial moisture content by drying in hot air oven at 130 °C. The five rubber sheet which dimension of 45x90 cm^2, used as the drying sample were hung with a bamboo rod in the drying chamber. Fig.1 shows the drying equipments and the position of temperature measurements. The hot air is sent along the aluminum duct in the bottom of drying chamber and the outlet hot air is circulating in the system. The experiment sets up by five rubber sheets, which hung in the drying chamber. The weight of rubber sheets were recorded using two hook balances. The surface temperature of rubber sheet was measured using J type thermocouples and the control temperature was measured with k type thermocouples at the temperature control 40, 50 and 60 °C. The heat sources from the burning of coconut charcoal briquette and LPG were transferred to aluminium pieces. The hot air was blown using 220 v axial fan and was supplied to the drying chamber.

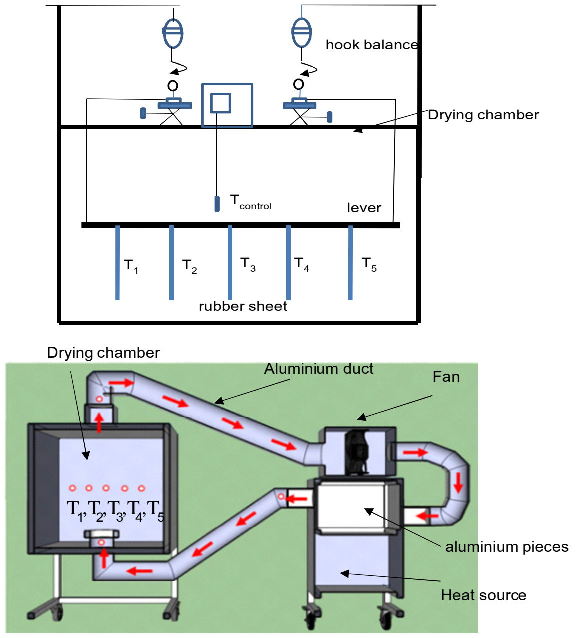

Fig. 1 Schematic diagram of drying equipments

2.2 Mathematical modeling of drying curves

The mathematical models used in the literature are illustrated in the table1. The moisture content can be determined from eqution1. Because of the initial moisture of rubber sheet did not equal so to compare drying kinetics, the moisture of rubber sheet is normalized and shown in moisture ratio (MR). The moisture ratio is calculated using equation 2 and M_{eq} can be determined from Halsey model using equation 3. [11]

$$MC = \frac{W_i - W_d}{W_d} \qquad (1)$$

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

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

where W_i is the initial weight

W_d is the dry weight

$M_{(t)}$ is sheet moisture at time t

M_i is initial moisture of sheet rubber

M_{eq} is a moisture equilibrium

RH is a relative humidity

A,B,C,D are constants

T is a temperature in Kelvin

Due to M_{eq} much less than $M_{(t)}$ and M_i so MR can be approximate as the ratio of $M_{(t)}$ and M_i.

Table1. Different empirical model for rubber sheet drying

No	Name	Model	Eq. No.	Ref
1	Page	$MR=\exp(-kt^n)$	(4)	[8]
2	Midili	$MR=a\exp(-kt^n)+bt$	(5)	[9]
3	Modified Henderson and Pabis	$MR=a\exp(-kt)+b\exp(-gt)+c\exp(-ht)$	(6)	[10]
4	Weibull Distribution	$MR=a-b\exp(-(kt^n))$	(7)	[3]

The nonlinear regression, the least square was employed to evaluate the parameters of the models. The quality of the adjustment was given by using the statistical parameters (R^2, χ^2) those parameters can be described in the equation8-9. [12]

$$\chi^2 = \frac{\sum_{i=1}^{n}(MR_{exp,i} - MR_{pre,i})^2}{n - z} \quad (8)$$

$$R^2 = \frac{\sum_{i=1}^{n}(MR_{pre,i} - \overline{MR}_{pre,i})^2}{\sum_{i=1}^{n}(MR_{exp,i} - \overline{MR}_{exp,i})^2} \quad (9)$$

3. Results and Discussion

The temperature of LPG source for the rubber sheet (RB1, RB3, and RB5) was more constant than the burning coconut charcoal briquette because of the burning of charcoal briquette could not control, while LPG source can be controlled the gas flow rate as shown the Fig. 2 and 3. The temperature reached in the beginning due to the heat exchange between rubber sheet and hot air. The temperature of biomass from burring charcoal briquette was swing very much so it expected that LPG source will be better to study the drying kinetic.

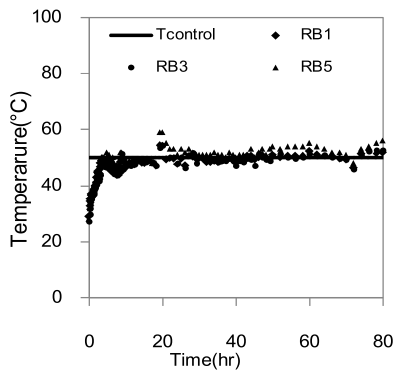

Fig. 2 The variation of temperature for rubber sheet used heat from LPG source.

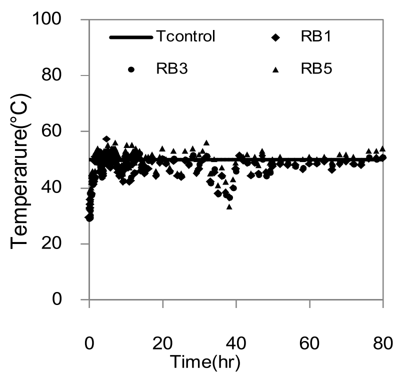

Fig. 3 The variation of temperature for rubber sheet used heat from biomass source.

3.1 Drying kinetics and modeling

The moisture ratio of sheet rubber was reduced rapidly when the temperature increased as shown in the Fig. 4. The initial moisture of the rubber was in the range of 64.77-86.46% dry basis and the final moisture content was in the range of 7-8% dry basis respectively. The comparison of model and experimental found that model of modified Henderson and Pabis is suitable for rubber sheet drying which has the highest R^2 and lowest the χ^2. The comparion of modeling and experimental results are shown in the Fig.5. The statistical is shown in Table. 2-4.

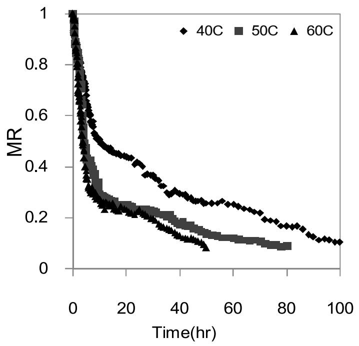

Fig. 4 Comparison of MR at different temperature

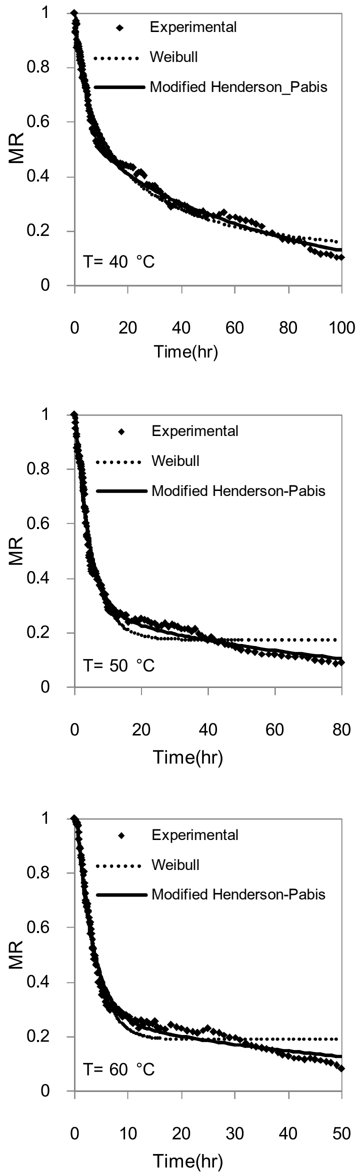

Fig. 5 Comparison of modeling and experimental result using LPG at 40, 50 and 60 °C.

Table. 2 Statistical results of curve fitting using LPG at 40 ℃

Model	Parameter	R^2	χ^2
Page	k=0.0217 n=0.5956	0.9691	0.0015
Midili	a=0.9390 b=0.0001 n=0.0237 k=0.0477	0.9671	0.0016
Modified Henderson and Pabis	a=0.2730 b=0.2476 c=0.4766 g=0.0002 h=0.0032 k=0.0002	0.9902	0.0005
Weibull Distribution	a=0.2806 b=-0.7283 k=0.0056 n=0.8198	0.9847	0.0007

Table. 3 Statistical results of curve fitting using LPG at 50 ℃

Model	Parameter	R^2	χ^2
Page	k=0.0217 n=0.5956	0.9253	0.0052
Midili	a=0.9921 b=0.0001 n=0.0339 k=0.0681	0.9654	0.0024
Modified Henderson and Pabis	a=0.1427 b=0.1122 c=0.7909 g=0.0001 h=0.0038 k=0.0013	0.9851	0.0011
Weibull Distribution	a=0.2121 b=-0.7808 k=0.0011 n=1.204	0.9849	0.0010

Table. 4 Statistical results of curve fitting using LPG at 60 ℃

Model	Parameter	R^2	χ^2
Page	k=0.0217 n=0.5956	0.9691	0.0015
Midili	a=1.0219 b=0.0001 n=0.0383 k=0.0768	0.9488	0.0039
Modified Henderson and Pabis	a=0.1514 b=0.1189 c=0.8348 g=0.0002 h=0.0053 k=0.0002	0.9869	0.0010
Weibull Distribution	a=0.1902 b=-0.8556 k=0.0017 n=1.1702	0.9815	0.0014

3.2 The drying kinetic of moisture ratio compares between experiment and simulation

In this section, the effective moisture diffusivity (D_{eff}) is determined from experimental drying curve at the control temperature 50 ℃. The governing equation is described by the Fick's law for the moisture concentration (c) in biological materials can be express as:

$$\frac{\partial c}{\partial t} = \nabla\left[-D_{eff}(\nabla c)\right] \tag{10}$$

The assumptions for this study are based on uniform initial temperature gradients, negligible external resistance, temperature gradients, shrinkage during drying, and constant diffusion coefficient after that apply the thin layer drying, and infinite slab sheet model which the thickness is smaller than the length of slab sheet and drying time is large. So, the approximation solution [3] of Eq. 10 under these conditions can be made:

$$\ln(MR) = \ln(\frac{8}{\pi^2}) - \frac{4\pi^2 D_{eff} t}{L^2} \qquad (11)$$

where, t is drying time, L is a half thickness of the slab sheet (3mm). Therefore, the effective diffusivity can be calculated from the slope of the plot $\ln(MR)$ vs. time. The result of the effective diffusivity of rubber which has the best fit (Hendersion and Pabis) at the temperature control 50 °C is 2.27x10^{-9} m^2/hr.

After the important parameter is obtained, the simulation study of the convection drying of a rubber sheet is carried out by FEM simulation software named COMSOL. This simulation also models the moisture concentration in the rubber sheet. In this regard, drying yield is a quantity that measures how much moisture, in percent, remains in the rubber sheet after drying process. Moreover, the moisture concentration also influences the temperature field by heat loss due to vaporization and also by changing the rubber sheet's thermal conductivity.

3.2.1 Model definitions

This model couples time-dependent interfaces describing the temperature and moisture concentration, respectively. The simulation does not model the convective velocity field outside the rubber sheet because the coefficient for convective heat and moisture transfer to the surrounding air are given. The model defines the geometry of the rubber sheet in 2-dimension. The width is 3.0 mm and the length is 40.0 cm. Physics are used in this model composed of General Heat Transfer (GHT) module and Diffusion module. For GHT module, the governing equation for is shown as:

$$\rho c_p \frac{\partial T}{\partial t} + \nabla \bullet (-k \nabla T) = 0 \qquad (12)$$

where, ρ is the density (917kg/m^3)[6], c_p is specific heat capacity (J/kg.K)[6], and k is thermal conductivity (W/m.K).

Assume symmetry for the temperature and air convection adds heat on all boundaries, the initial temperature of rubber sheet equals to 27˚C, also the boundary conditions for the heat transfer interface is shown as:

$$\hat{n} \bullet (k \nabla T) = h_T (T_{\inf} - T) + \hat{n} \bullet (D_m \lambda \nabla c) \qquad (13)$$

where, h_T is the heat transfer coefficient (25 W/m^2.K[7]) $T_{\inf}$ is the drying chamber air temperature (50˚C), D_m is the surface moisture diffusion coefficient (5x10^{-10}m^2/s), and λ is the molar latent heat of vaporization (2.3x10^{6}J/mol[7]). The vaporization of water at the rubber sheet's outer boundaries generates a heat flux out of the sheet. Represent this heat flux with the second term of Eq. (13).

For the diffusion module, the governing equation is shown in Eq. (10), by assuming the initial moisture concentration is 78% of rubber sheet density and D_{eff} equals to 2.27x10^{-9} m^2/hr. The boundary conditions for the diffusion are:

$$\hat{n} \bullet (D_{eff} \nabla c) = k_c (c_b - c) \qquad (14)$$

Where, k_c is mass transfer coefficient ($k_c = h_m / \rho C_m$, m/s), h_m is the mass transfer coefficient in mass unit (1.67x10^{-7} kg/m^2.s), c_m is the specific moisture capacity ($6x10^{-3}$ kg moisture/kg rubber sheet), c_b is air (bulk) moisture concentration (18.34kg/m^3), and c is the moisture concentration in rubber sheet.

The simulation results carried out by COMSOL software and compared to the experimental results of rubber sheet with LPG as a heat source at control temperature 50 °C are shown in Fig. 6. In this figure, the simulation can picks up trend on the moisture ratio when compares to the experiment; however, the simulation yield underpredict experiment. In the case of temperature, the simulation shows overpredict in the first twenty hours of the drying time then it fits very well the experiment as the simulation line pass through the error bar of experiment in the last drying time.

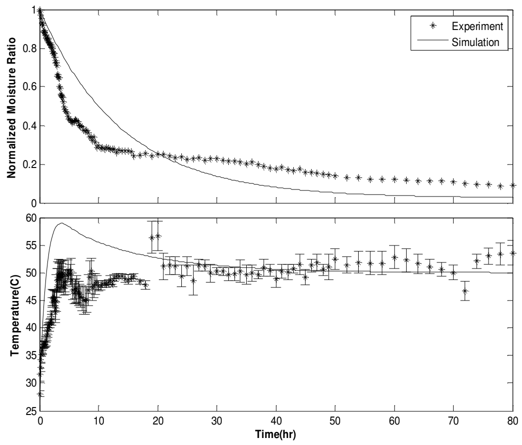

Fig. 6 The simulation results compared to experimental results of normalized moisture ratio and temperature of rubber sheet with LPG heat source at control temperature 50 °C as a function of drying time.

4. Conclusion

The drying kinetic of five rubber sheet was studied by using different heat source. The LPG source was suitable for controlling temperature than biomass source. From the curve fitting, it suggests that the model of Modified Henderson and Pabis has the best fit. Then the effective diffusion coefficient has been defined for rubber sheet with LPG heat source at control temperature 50 °C. This important parameter used to simulate the drying kinetic of drying rubber sheet by using COMSOL. Finally, the simulation results showed the good tendency to predict the experiment results of drying rubber sheet for both drying temperature and moisture ratio but simulation yield over predict and under predict respectively.

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