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Empirical Modeling of Air Dried Rubberwood Drying System

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***Abstract*—**Rubberwood is a crucial commercial timber in Southern Thailand. All processes in a rubberwood production depend on the knowledge and expertise of the technicians, especially the drying process. This research aims to develop an empirical model for drying kinetics in rubberwood. During the experiment, the temperature of the hot air and the average air flow velocity were kept at 80-100 °C and 1.75 m/s, respectively. The moisture content in the samples was determined less than 12% in the achievement of drying basis. The drying kinetic was simulated using an empirical solver. The experimental results illustrated that the moisture content was reduced whereas the drying temperature and time were increased. The coefficient of the moisture ratio between the empirical and the experimental model was tested with three statistical parameters, R-square (R^2), Root Mean Square Error (RMSE) and Chi-square (χ^2) to predict the accuracy of the parameters. The experimental moisture ratio had a good fit with the empirical model. Additionally, the results indicated that the drying of rubberwood using the Henderson and Pabis model revealed the suitable level of agreement. The result presented an excellent estimation (R^2 = 0.9963**)** for the moisture movement compared to the other models. Therefore, the empirical results were valid and can be implemented in the future experiments**.**

***Keywords*—**Empirical models, hot air, moisture ratio, rubberwood.

I. Introduction

CURRENTLY, wood resources are quite limited due to the demand increasing whereas the supply remains constant or decreases. Industry sectors using wood seek to improve their manufacturing processes and look for alternative wood species, among by-products from agriculture sectors [1]. Rubberwood is a fast-growing tree that makes a highly-attractive investment to some investors. The growing demand of rubberwood from relevant industries requires alternative trees to compensate for the natural regeneration of rubberwood. The rubberwood is commonly cut down when its age is between 20 to 30 years depending on the type of the rubberwood and when its trunk diameter is less than 200 mm [2]. The rubberwood is naturally short in length and has to be glued during the manufacturing processes to make a useful wooden board. One of the important methods of wood preserving is drying which has to do with the complex combination of the heat treatment and the removal of moisture content (MC) [3]. In general, the conventional drying process of rubberwood in Thailand takes 5-8 days due to the low thermal efficiency of the dryer and the seasonal variation [4]. The goal of drying is to eliminate liquid inside the dried sample without generating any destruction to the wood samples. Moisture can leave the surface at initial condition depending on many parameters. To finish a proper drying of timber, it requires a method that eliminates the moisture from the inside of the dried wood to the surface at the same rate as the evaporation of surface moisture. Predicting MC distribution after lumber drying is beneficial to the industry for determining the percentage of wet lumber. The model of wood drying was validated with experimental data measured in a laboratory drying kiln. Experimental data from the drying curves can be used in the simulation of wood drying to optimize the drying process [5]. Many mathematical models have been used to describe drying process. All parameters used in simulation models are directly related to the drying conditions. The aim of this study is to determine the kinetic drying of rubberwood by using hot air dryer. Empirical modeling is used to describe the drying behavior of rubberwood.

Mathematical Modeling

Moisture ratio (MR) is dimensionless MC and is defined as: [6]

$$MR = \frac{m - m_e}{m_o - m_e} \tag{1}$$

where m is the MC at time t, m_0 is the initial MC, and m_e is the equilibrium MC. In certain drying processes, materials are not continuously exposed to relatively uniform humidity and temperature conditions [7].

From Table I, it can be seen that all types of mathematical model have always been used together with the result of the drying process for the agricultural products [8], [9].

II. Material and Method

In this work, drying of rubberwood was investigated experimentally and numerically. In the experiment, the rubberwood sample which is 7.6 mm in width, 25 mm in thickness and 1,100 mm in length was dried in hot air dryer [7]. The hot air dryer unit with temperature controller consists of a blower, a 3-kW electric heater, and a valve.

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TABLE I
EMPIRICAL MODELS TO DESCRIBE DRYING KINETICS

Model name	Model equation	Reference
Page	$MR = [(M-M_e) / (M_0- M_e)] = \exp(-k.t^n)$	[8]
Henderson and Pabis	$MR = [(M-M_e) / (M_0- M_e)] = a \cdot \exp(-k.t)$	[9]
Logarithmic	$MR = [(M-M_e) / (M_0- M_e)] = a \cdot \exp(-k.t) + c$	[10]
Two-term Exponential	$MR = [(M-M_e) / (M_0- M_e)] = a \cdot \exp(-k.t) + (1-a) \exp(-k.a.t)$	[11]
Diffusion Approximation	$MR = [(M-M_e) / (M_0- M_e)] = a \cdot \exp(-k.t) + (1-a) \exp(-k.b.t)$	[12]

The blower with adjustable speed to control air flow velocity is used to generate air flow for heat convection. The blower with temperature control and electric heaters is connected to the chamber through a uniform flow filter (Fig. 1). The airflow was measured with an anemometer (Model DIGICON DA-45S). The internal and external temperatures of rubberwood were detected by K-type thermocouples and a data logger as illustrated in Fig. 2. The weight loss of wood during drying was measured with a load cell to calculate the MC (Fig. 3). The temperatures of hot air were 80, 90 and 100 °C and the hot air velocity was 1.75 m/s [13]. The temperature profiles and the drying rates of three samples were observed. These properties were obtained by measuring the weight of the wood board after each period of drying.

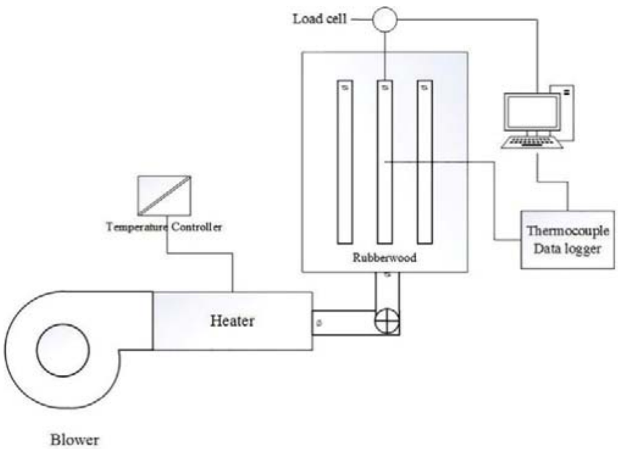

Fig. 1 Experimental setup and measurement diagram

Fig. 2 Hot air dryer in lab-scale

Fig. 3 Wood samples and load cell weight measurement

Statistical Analysis

The statistical parameters to assess this model were proved by the correlation parameter (R^2) for selection of the best model. The relationship between the computed and experimented MR was compared with three statistical parameters, R^2, RMSE and Chi-square (χ^2). The comparison would indicate the prediction accuracy of the parameters and the model for the rubberwood MR with three different temperature levels [14]. These parameters were calculated as:

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

$$RMSE = \left[\frac{1}{N} \sum_{n=1}^{N} (MR_{pre,n} - MR_{exp,n})^2 \right]^{1/2} \quad (3)$$

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

where $MR_{exp,n}$ is the experimental MR of n^{th} data, $MR_{pre,n,}$ is an estimated MR of n^{th} data, $\overline{MR_{pre,n}}$ is the mean value of $MR_{pre,n}$, N is the number of observations, and z is the number of constants in the drying model. High R^2 with low *RMSE* and χ^2 indicate better fit with the model.

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III. Results and Discussion

A. Drying Kinetics

The rubberwood was dried at 80, 90, and 100 °C in the hot air dryer. The experiments were fitted with five models as shown in Table I. The MR, as seen in (1), encourages in studying the drying behavior. The effect of drying air temperature on the MR decreased gradually from the initial MC to final MC within 40 hours. The graphs of the variation of MR of rubberwood with drying time are shown in Figs. 4-6. In Figs. 4-6, the MR during the initial period of drying is decreased quickly. The reason is that the free water in the wood is removed from the surface layer of the samples. Later, bound water removal begins after the free water has been completely removed. Thus, the MR decreased slowly over the last period. Fig. 7 shows the acceptable color and deformation of dried rubberwood. The statistical results of five models, including the drying model coefficients, the comparison criteria used to evaluate the goodness of fit, R^2 (2) to explain representation of the model, RSME (3) to show the accuracy of model prediction and χ^2 (4) for the model fitness, are summarized in Table II. The values of the selected model coefficients (k, a, n, c) are shown in Table II. The models were evaluated based on R^2, χ^2, and RMSE. The best model to predict the drying process would obtain the highest value of R^2 and lowest values of χ^2 and RMSE. The Henderson and Pabis model ($R^2 = 0.9963$, $\chi^2 = 0.000399$, $RMSE = 0.000155$) was the best descriptive model for all treatments. Thus, it was accepted to represent the characteristics of rubberwood drying by hot air.

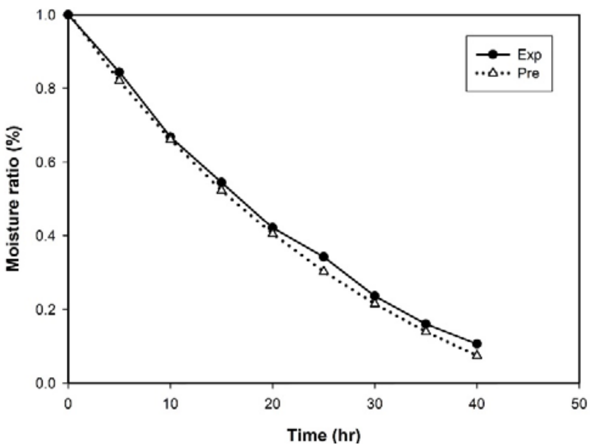

Fig. 4 Comparison of experimental MR and predicted MR from the Logarithmic model at 80 °C

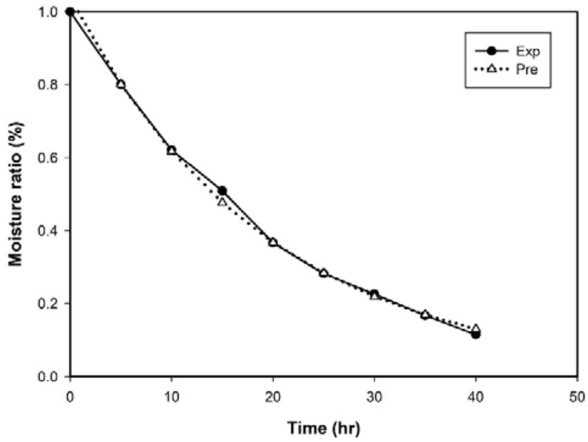

Fig. 5 Comparison of experimental moisture ratio and predicted moisture ratio from the Henderson model at 90 °C

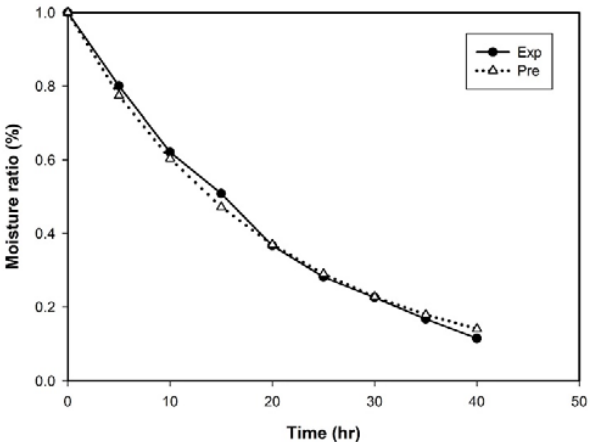

Fig. 6 Comparison of experimental moisture ratio and predicted moisture ratio from the Page model at 100 °C

Fig. 7 The acceptable color and deformation of dried rubberwood

TABLE II
THE MODEL OF MR ACCORDING TO DIFFERENT DRYING MODELS

Model name	Temperature (°C)	Coefficients	R^2	χ^2	*RMSE*
Page	80	k=0.0007, n=0.9899	0.9800	0.0018	0.00069
Henderson & Pabis	80	k=0.0008, a= 1.038	0.9874	0.0013	0.00050
Logarithmic	80	k=0.0005, a=1.3331, c= -0.327	0.9939	0.00069	0.00027
Two-term Exponential	80	k=0.0007, a=0.9898	0.9805	0.00215	0.00083
Diffusion Approximation	80	k=0.0007, a=0.9598, b=0.0573	0.9834	0.95989	0.05732
Page	90	k=0.0008, n=0.9851	0.9921	0.00075	0.00029
Henderson & Pabis	90	k=0.0008, a=1.038	**0.9963**	**0.00039**	**0.00015**
Logarithmic	90	k=0.0005, a=1.3159, c= -0.327	0.9932	0.00076	0.00029
Two-term Exponential	90	k=.00078, n=0.9898	0.9939	0.00054	0.00021
Diffusion Approximation	90	k=0.0007, a=0.9598, b=0.2745	0.9837	0.00348	0.00135
Page	100	k=0.0009, n=0.9789	0.9952	0.00046	0.00018
Henderson & Pabis	100	k=0.0008, n=1.0381	0.9909	0.00094	0.00036
Logarithmic	100	k=0.0005, a=1.3331, c= 0.327	0.9918	0.00094	0.00036
Two-term Exponential	100	k=0.0007, a=0.9898	0.9939	0.00054	0.00021
Diffusion Approximation	100	k=0.00078, a=0.958, b=0.2745	0.9837	0.00348	0.00135

IV. CONCLUSION

This study presents an empirical model to describe the moisture desorption curves compared with an experimental investigation of the hot air drying of rubberwood under different conditions. The experimental results were further analyzed to find the best suitable drying kinetic model for rubberwood drying. Different mathematical models were also determined with the drying behavior of rubberwood. The model of Henderson and Pabis was found to be the most suitable model for describing drying curve of the three conditions. Future research should study the physical properties of dried rubberwood.

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