

## DRYING CHARACTERISTICS OF PINE FOREST RESIDUES

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The thin layer drying of pine forest residues consisting of bark, needles, leaves, and chips was experimentally conducted at air temperatures of 40, 50, 60, 70, and 80°C. Physical and chemical properties of fractionated forest residues were determined to evaluate its fuel properties. The experimental data obtained from thin layer drying study were fitted with Lewis, Page, and Henderson and Pabis equations to evaluate the drying behavior of the forest residues. Among the three drying models, the Henderson and Pabis model fitted well with the experimental drying data at the tested temperatures (40, 50, 60, 70, 80°C), achieving  $R^2$  values of 0.992, 0.994, 0.997, 0.989, and 0.983, respectively. The drying constant  $k$  for the forest residues was increased with increase in drying air temperature and was correlated in the form of a second order regression equation. The thin layer drying data developed from this study will be useful for designing low temperature dryers for forest residues.

*Keywords:* Pine forest residues; Thin-layer drying; Physical properties; Fuel properties

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### INTRODUCTION

Forest residues consist of downed dead, culled trees, small stems, and unused portions of trees (tops, branches) left in the woods after logging operation (Helms 1998). They are considered to be one of the largest potential sources of forest biomass that have not yet been utilized for any bioenergy application. In the United States approximately 60 million dry tons of unutilized biomass is available at harvest sites annually based on the 2002 Forest Inventory Analysis (FIA) data (Smith et al. 2004). Current logging operations leave the residues at the logging sites to maintain the soil conditions, but excessive amount are burnt, which sometime causes forest fires and environmental pollution. Although forest residues can be potentially used for direct combustion, gasification, and even for producing wood pellets, they are difficult to collect, transport, and store both in terms of economics and safety, due to high moisture content (40-60% wb), low bulk density, and low energy content (Moreno et al. 2004; Mani 2005; Mani et al. 2006b). In direct combustion boilers, dry fuel results in improved efficiency, higher combustion flame temperature, reduced fuel use, and lower gaseous emissions (Tillman 2000). For pelleting applications, the optimum moisture content of the biomass should usually be from 7% and 14% (wb) (Stahl et al. 2004; Amos 1998). Artificial drying of forest residues is crucial to store the material safely and to utilize it efficiently for thermal applications.

Forest residues consist primarily of bark, needles, leaves, and sap and heart wood chips. They vary in composition and drying characteristics. The chemical analysis of

Douglas fir wood bark and needles indicated that bark and needles contain much more extractives and lignin (phenolic compounds), which have a higher heat of combustion, and with lower amount of cellulose and hemicelluloses, which have a lower heat of combustion (Shafizadeh et al. 1976). Usually, barks contain higher ash content due to soil contamination during harvesting (Harkin and Rowe 1971). Currently, rotary drum dryers, fluidized bed, and moving bed dryers are commercially used to dry clean chips and sawdust for making wood pellets (Mani et al. 2006a, b). However, such dryers are expensive and cannot be usable in the field/forest or at a small scale. In-bin/deep bed drying of forest residues using low temperature drying air can be possible in the field, as the operation is similar to that of grain dryers and the cost is low. Design and modeling of such dryers requires knowledge of drying kinetics and moisture loss characteristics of forest residues.

Numerous drying models have been proposed to describe thin layer drying of biological materials (Jayas et al. 1991). Most of the studies on thin layer drying have been carried out for agricultural crops (Greig 1990). In addition, there has been study of some biomass feedstocks such as corn (Tolaba and Suarez 1988), alfalfa (Patil et al. 1992), flax fiber (Ghazanfari et al. 2006a, b), willow chips and stems (Gigler et al. 2000a; Gigler et al. 2000b), olive husk (Celma et al. 2008), and bagasse (Vijayaraj et al. 2007). Although drying characteristics of wood logs and sawdust have been studied by several researchers, there is a limited literature on the drying behavior of forest residues. Physical characteristics of forest residues are also unknown for thermal applications. The main objectives of this study were to determine the physical and chemical properties of pine forest residue fractions, to experimentally determine the thin layer drying kinetics of bulk forest residues at various temperatures, and to fit the experimental data in various thin layer drying models to best predict the drying behavior of forest residues.

## **EXPERIMENTAL**

### **Materials**

Southern yellow pine forest residues were collected from a regular logging operation during May, 2008 near Macon, GA, USA. The residues were chipped using a whole tree chipper and subsequently transported to Athens, GA. They were kept in the freezer at minus  $11 \pm 2$  °C in a plastic container with a lid to avoid any microorganism growth and a possible loss of volatile compounds. The initial moisture content of pine forest residues was about 50% (wb) at the time of collection and storage.

### **Sample Preparation and Analyses**

The chipped forest residues were initially dried using a convective oven to remove surface moisture and used for determining the mass fractions and physical and chemical properties of each fraction. A large volume of forest residues was divided into five samples. Each sample of 100g was manually separated into five mass fractions: chips (sap and heart wood), small stems, barks, leaves, and small particles. Most of the leaves and needles were ground into small particles during the chipping operation and were usually less than 5 mm in size. Each fraction was weighed using an analytical balance

with an accuracy of  $\pm 0.0001$  g (CHYO, Jex120, Japan), and the analysis was repeated five times.

The size distribution of the chips, small stems, barks, and leaves were measured using a digital caliper with an accuracy of  $\pm 0.01$  mm, (Mitutoyo, Kanagawa, Japan). Fifteen samples from each fraction were drawn randomly to measure sample dimensions.

The initial moisture content of bulk forest residue was measured as per the ASABE standard (ASABE 2008) S358.2 using a convective oven at  $103^{\circ}\text{C}$  for 24 hrs. The weight loss from the initial sample weight was reported as moisture content of the sample on a wet basis (wb).

Bulk density of forest residues was determined using a cylindrical container of known volume. Samples were bone dried and were poured from a height of 0.6 m into the container. The top surface of the container was leveled, and the filled container was weighed. The bulk density was calculated as a ratio of the mass of the sample to volume of the container, and this was repeated five times (Mani et al. 2004). Due to the small amount of each mass fraction, bulk density of each mass fraction was not measured.

Proximate analysis, ultimate analysis, and heating values of each fraction of forest residues were determined using standard procedures. A proximate analyzer (TGA-701, LECO Corporation, Michigan, US) was used to determine the moisture content, total volatile matter, ash, and fixed carbon. An ultimate analyzer (LECO Corporation, Michigan, US) was used to determine the elemental compositions such as carbon, hydrogen, nitrogen, sulfur, and oxygen. The heating value of the samples was determined using a bomb calorimeter (LECO Corporation, Michigan, US).

### **Thin Layer Drying Experiment**

A thin layer drying experiment of forest residues was performed at five different air temperatures (40, 50, 60, 70, and  $80^{\circ}\text{C}$ ) to evaluate the drying rate and kinetics of forest residues. A sample size of 50g wet forest residue was taken from the refrigerator and was thawed to room temperature before drying. The samples were spread in a single thin layer on an aluminum tray and were placed in a convective air oven at various pre-set air temperatures. The air flow rates during the experiment at each temperature were uniformly provided by a built-in fan at the back of the oven ranging from 0.3-0.35 m/s. The relative humidity for each set air temperature was recorded (23.9, 15, 9.6, 6.5, and  $4.2\% \pm 1$  respectively). The change of sample mass due to moisture loss was recorded at every 1 min during the first 30 min of drying, every 5 min for an hour, and every 10 min during the remainder of the test. Drying was continued until the change of the sample mass was less than 1% or no mass change was noticed. To decrease experimental error, each drying experiment was carried out in triplicate. After each test, the sample was oven-dried at  $103 \pm 2^{\circ}\text{C}$  to determine the final moisture content. From the experimental data, a drying curve for each sample at various drying air temperature was developed.

The equilibrium moisture content of pine residues at different drying temperatures used in the drying experiments was determined using Zuritz's sorption isotherm model. The model gave the best prediction of equilibrium moisture content for the wood between  $21.1$  and  $71.1^{\circ}\text{C}$  (Avramidis 1989).

$$EMC = \left[ \frac{-T \ln(1-h)}{C_1 \left(1 - \frac{T}{T_c}\right)^{C_2}} \right]^{\frac{1}{C_3 T^{C_4}}} \quad (1)$$

where  $T$  is temperature (K),  $h$  is relative humidity expressed in proportion,  $T_c$  is the critical temperature of water (647.1 K), and  $C_1$ , -6.64,  $C_2 = 0.13$ ,  $C_3 = 1.10 \times 10^2$ , and  $C_4 = -0.75$ .

### Thin Layer Drying Models

The thin layer drying experimental data were fitted with three different thin layer drying models that have been successfully used in agricultural crops and biomass feedstocks (Midilli and Kucuk 2003; Pathak et al. 1991; Shei and Chen 1998; Vijayaraj et al. 2007; Yang et al. 2007). They are the Lewis (Lewis 1921) [eq. 2], the Page (Page 1949) [eq. 3] and the Henderson and Pabis (Henderson and Pabis 1961) [eq. 4] equations. The Lewis equation assumes negligible internal resistance, which means no resistance to moisture movement from within the material to the surface of the material. This equation was primarily used by several researchers because it is simple. Page's equation is a modification of the Lewis equation and has been reported to adequately predict the thin layer drying of bagasse (Vijayaraj et al. 2007), Pistachio (Midilli and Kucuk 2003), peanuts (Yang et al. 2007), and rapeseeds (Pathak et al. 1991).

The Henderson and Pabis model was developed based on the approximation that diffusion controls the drying process. This model has been used to describe various agricultural materials. The slope of this model,  $k$ , is related to effective diffusivity, when drying takes place only in the falling rate period and liquid diffusion controls the process.

$$\text{Lewis Equation:} \quad MR = \left( \frac{M - M_e}{M_o - M_e} \right) = \exp(-kt) \quad (2)$$

$$\text{Page Equation:} \quad MR = \left( \frac{M - M_e}{M_o - M_e} \right) = \exp(-kt^n) \quad (3)$$

$$\text{Henderson \& Pabis Equation:} \quad MR = \left( \frac{M - M_e}{M_o - M_e} \right) = a \exp(-kt) \quad (4)$$

The thin layer drying models just described were fitted to the drying experimental data to determine the coefficients  $k$ ,  $a$ , and  $n$  at various drying air temperatures. The coefficient of determination ( $R^2$ ), residual mean square error ( $RMSE$ ), [eq. 5] and chi-square ( $\chi^2$ ), [eq. 6] were determined as the primary criteria for determining the goodness of the fit for the drying data (Özdemir and Onur Devres 1999). The coefficient of determination ( $R^2$ ) serves as a measure of the closeness of the relation to linearity, while

the *RMSE* and  $\chi^2$  represent the deviation between the predicted and experimental values. As a consequence, the best model exhibits the highest  $R^2$ , while the *RMSE* and  $\chi^2$  approaches to zero (Berger 1980).

$$\chi^2 = \frac{\sum_{i=0}^N \left( \sum_{i=0}^N (MR_{\text{exp},i} - MR_{\text{pre},i})^2 \right)^2}{N - n_p} \quad (5)$$

$$RMSE = \left( \frac{1}{N} \sum_{i=1}^N (MR_{\text{exp},i} - MR_{\text{pre},i})^2 \right)^{\frac{1}{2}} \quad (6)$$

## RESULTS AND DISCUSSION

### Physical and Chemical Properties of Forest Residues

Forest residues were fractionated into clean chips, bark, small stems, leaves, and small particles, and the mass distribution of the fractions is shown in Fig 1. More than half (51%) of the samples were chips, followed by 19% of small stems and 13% of bark. Leaves and small particles contributed about 9% and 8% respectively. Most of the small particles were pine needles ground up during the chipping operation. The dimensions of each component are given in Table 1. The size of small particles was less than 5 mm and was also widely distributed. The average bulk density of the whole forest residues was (on dry basis) 149.17 kg/m<sup>3</sup> (SD = 4.47), compared to sawdust of 142.2 kg/m<sup>3</sup> and clean pine chips of 209.8 kg/m<sup>3</sup> (Gigler et al. 2000a). The lower bulk density of forest residues was mainly attributed to uneven particle size distribution of small stems and leaves.

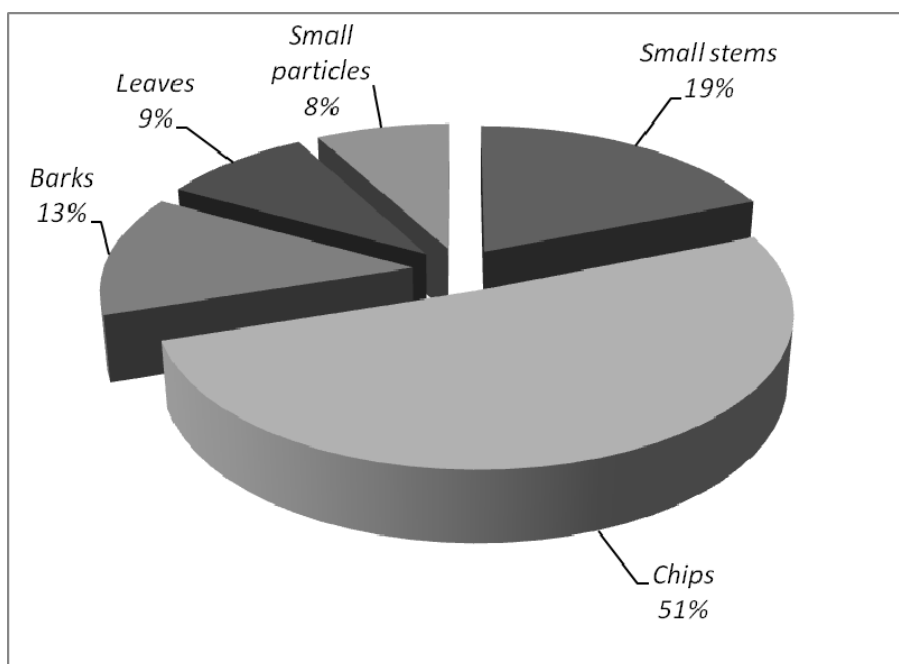
**Table 1.** Dimensions of Forest Residue Components

Residue fractions	Thickness <sup>a</sup> (mm)	Length <sup>a</sup> (mm)	Width <sup>a</sup> (mm)
Chips	6.3 (0.8)	26.1 (8.3)	18.5 (0.0)
Barks	4.4 (1.2)	32.0 (0.9)	15.0 (0.8)
Small stems	4.7 (0.5)	124.9 (93.3)	4.6 (0.2)
Leaves	0.5 (0.1)	93.0 <sup>b</sup> (28.2)	—
Small particles <sup>c</sup>	<4.8		

<sup>a</sup> Numbers in the parenthesis are standard deviation with five replications.

<sup>b</sup>The length of the leaves ranges from 36.1 to 124.1 mm.

<sup>c</sup>The size of small particles represents particles that are smaller than 4.8 mm screen size.



**Figure 1.** Mass distribution of pine forest residue fractions

Chemical compositions and heating values of whole forest residues and each fraction are given in Table 2. Bark contained significantly higher ash content (4.3%) compared to clean chips (1.5%), and the whole forest residues contained 2.4% ash content. Although there were no significant changes in the elemental composition and heating values among residue fractions and the whole forest residues, leaves contained the highest heating value and nitrogen content of 20.1 MJ/kg and 4.5% respectively. From the fuel stand point, the bulk forest residue provided a balanced composition of ash and nitrogen and an average heating value of 19.6 MJ/kg.

### Thin Layer Drying Experiment

Figure 2 shows the drying characteristics of forest residues at various drying temperatures. An increase in air temperature increased the drying rate and decreased the drying time. Similar drying behavior was observed for pine and willow chips (Moreno et al. 2004; Gigler et al. 2000b) and other lignocellulosic materials (Patil et al. 1992; Gigler et al. 2000a; Ghazanfari et al. 2006a). The rate of moisture loss in the beginning of the drying period was higher due to removal of surface moisture, and the rate was decreased as diffusion came to dominate the drying process. The rate of moisture loss became negligible as the material reached equilibrium with the drying air temperature, terminating further moisture losses. Low temperature drying can be beneficial for forest residues, as it can prevent loss of high energy value volatile compounds (Stahl et al. 2004), if low temperature heat sources are available at low cost. Deep bed or in-bin drying of forest residues using atmospheric air or low temperature air can be possible at the biomass source to improve the energy density of forest residues for thermal energy application. The final moisture content of pine residues at a given drying temperature was considered as equilibrium moisture content ( $M_e$ ) of forest residues and was also best predicted by Zuritz's sorption isotherm model (Eq. 1). This model was originally

developed to predict the equilibrium moisture content of wood between 21.1 and 71.1°C (Avramidis 1989).

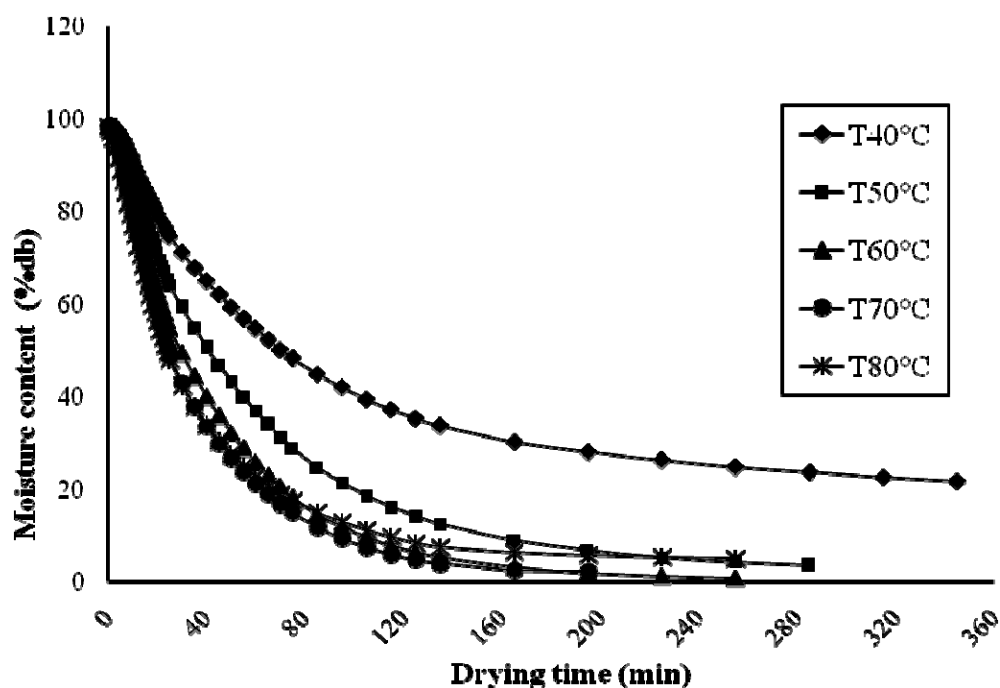


Figure 2. Drying rate of forest residues at various drying air temperatures

Table 2. Chemical and Fuel Properties of Forest Residue Fractions

Biomass	Pine forest residues	Leaves	Small particles	Small stems	Barks	Chips
<b>Proximate Analysis<sup>a</sup> (% dry basis)</b>						
Volatile	80.5 (0.4)	78.3 (0.3)	79.3 (0.6)	79.6 (1.4)	72.9 (0.2)	85.4 (0.2)
Ash	2.4 (0.1)	3.87 (0.2)	3.44 (0.2)	2.9 (0.4)	4.3 (0.2)	1.5 (0.2)
Fixed Carbon	17.1 (0.3)	17.9 (0.2)	17.3 (0.4)	17.4 (1.0)	22.9 (0.2)	13.1 (0.2)
HHV (MJ/kg)	19.6 (0.2)	20.2 (0.2)	19.4 (0.1)	19.1 (0.1)	19.1 (0.1)	19.5 (0.1)
<b>Ultimate Analysis<sup>a</sup> (% dry basis)</b>						
Carbon	45.9 (0.5)	49.6 (0.3)	47.9 (0.4)	47.0 (0.6)	47.9 (0.4)	47.7 (0.5)
Hydrogen	5.9 (0.2)	6.9 (0.1)	6.4 (0.1)	6.4 (0.2)	5.9 (0.1)	6.7 (0.1)
Oxygen	43.5 (0.6)	35.2 (1.0)	39.6 (0.5)	40.8 (0.8)	38.9 (0.2)	41.0 (1.4)
Nitrogen	2.3 (0.4)	4.5 (0.8)	2.7 (0.2)	2.9 (0.3)	3.0 (0.3)	3.0 (1.0)
Sulfur	-	0.1	-	-	-	0.1

<sup>a</sup> Numbers in the parenthesis are standard deviation with three replications.

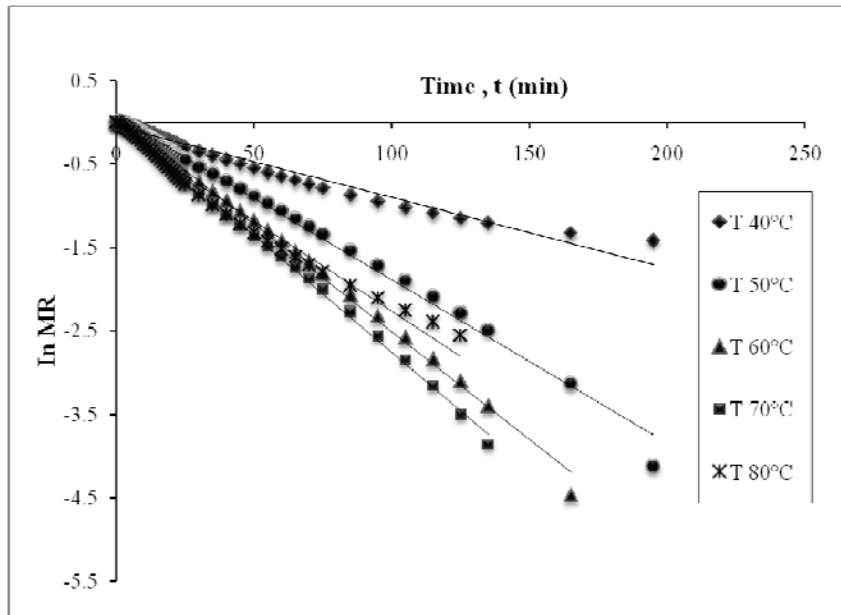
### Thin Layer Drying Models

Thin layer drying experimental data were used to predict the drying characteristics of forest residues using the Lewis, the Page, and the Henderson and Pabis equations. The moisture ratio (MR), a dimensionless parameter, was calculated from instantaneous moisture content (% db) at any given time, initial moisture content (% db), and the equilibrium moisture content (% db) and was fitted with different thin layer drying models using a Microsoft Excel Solver. The results from statistical analysis ( $R^2$ ,  $\chi^2$  and  $RMSE$ ) given in Table 3 were used to decide on the best fitted model. The best model was selected based on the highest  $R^2$  and the lowest  $\chi^2$  and  $RMSE$  values (indicated in bold letters).

Among the three models, the Henderson and Pabis model fitted the best with experimental drying data for forest residues, with the biggest  $R^2$  for all temperatures.  $\chi^2$  and  $RMSE$  also showed best results with the smaller values during 40-60°C but were slightly greater at high temperatures (70 and 80°C). The Lewis and Page equations fitted fairly well with the experimental drying data in the temperature ranges of 50-80°C. But both of the models did not predict the drying behavior of forest residues at low temperature (40°C). The Page's coefficient, ( $n$ ) obtained for the pine residues showed that the value of  $n$  increased with increase in drying air temperature, except at 80°C, where it was slightly reduced. Figure 3 shows the relationship between the predicted and experimental drying curves for forest residues at various temperatures using the Henderson and Pabis model. The deviations in the Henderson and Pabis model parameters were the smallest, as shown in Table (3), compared to other two models, indicating that the moisture loss from the residues mainly was dominated by liquid diffusion. The drying constant,  $k$  characterizes the rate of moisture removal from the material per unit time. It is in units of  $\text{time}^{-1}$ , relating to effective diffusivity when the drying process takes place only in the falling rate period and only liquid diffusion controls the process (Henderson and Pabis 1961).

An increase in drying air temperature resulted in an increased drying rate, but it was independent of air flow rate when the air velocity exceeded 0.25 m/s (ASABE 2008). In all drying experiments, the air velocity was always maintained higher than 0.25 m/s for consistent results. The  $k$  value for forest residues increased with increase in the drying air temperature and stabilized at 80°C as shown in Fig 4. Similar trends of  $k$  values were observed for all three models. The larger value of  $k$  resulted in a higher drying rate (Jayas et al. 1991). In the study of flax fiber drying (Temperature 30°C - 70°C), it was found that the  $k$  value ranged from 0.0059 to 0.0214  $\text{min}^{-1}$  (Ghazanfari et al. 2006a). The  $k$ -values in the temperature range of 60°C to 80°C in thin layer drying for alfalfa stem were in the range of 0.0098-0.0511 (Patil et al. 1992). While comparing  $k$ -values, pine forest residues can be dried faster than flax fiber but slower than alfalfa stem at low temperature ranges (40-70°C).





**Figure 3.** Henderson and Pabis model fitting with experimental drying data for forest residues

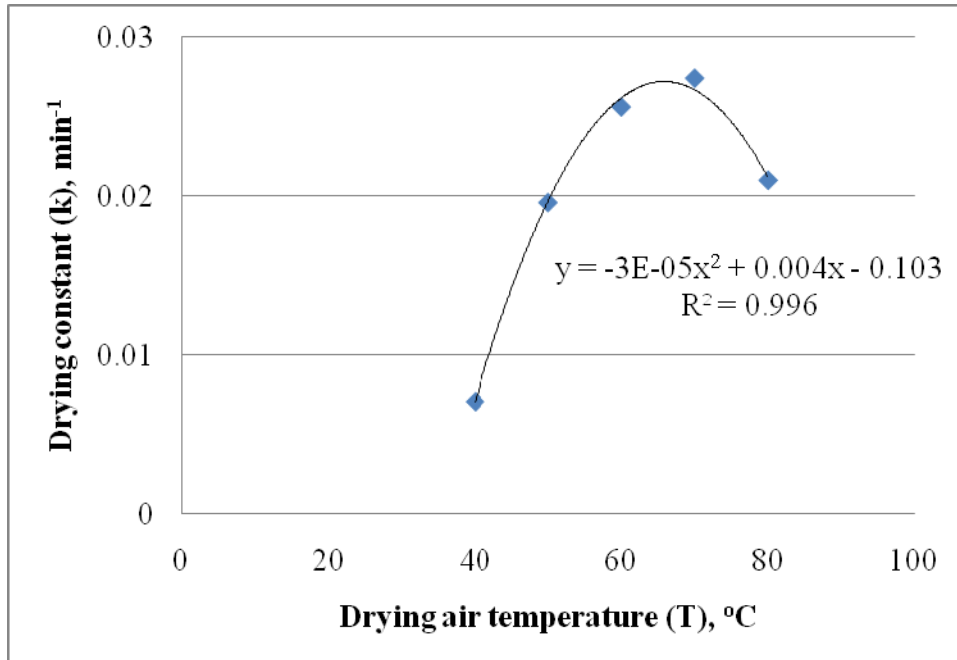
**Table 3.** Thin Layer Drying Model Parameters for Forest Residues at Various Drying Air Temperature

Model		Air Temperature				
		40 °C	50 °C	60 °C	70 °C	80 °C
Lewis equation	$MR = \exp(-kt)$					
	$k$	0.0079	0.0189	0.0248	0.0270	0.0226
	$R^2$	0.9203	0.9847	0.9851	0.9632	0.9490
	$\chi^2$	<b>0.0044</b>	0.0014	0.0018	0.0036	0.0045
	RMSE	0.0632	0.0352	0.0393	0.0578	0.0583
Page equation	$MR = \exp(-kt^n)$					
	$n$	1.1816	1.3093	1.3724	1.2717	1.0961
	$k$	0.0047	0.0051	0.0060	0.0103	0.0181
	$R^2$	0.8990	0.9475	0.9619	0.9714	0.9675
	$\chi^2$	0.0039	0.0016	0.0022	<b>0.0022</b>	<b>0.0019</b>
	RMSE	<b>0.0612</b>	0.0393	0.0461	<b>0.0417</b>	<b>0.0386</b>
Henderson and Pabis	$MR = a \cdot \exp(-kt)$					
	$a$	0.9097	1.0758	1.0707	1.0319	0.9044
	$k$	0.0071	0.0196	0.0256	0.0274	0.0211
	$R^2$	<b>0.9919</b>	<b>0.9942</b>	<b>0.9970</b>	<b>0.9887</b>	<b>0.9827</b>
	$\chi^2$	<b>0.0044</b>	<b>0.0011</b>	<b>0.0013</b>	0.0040	0.0050
	RMSE	0.0635	<b>0.0307</b>	<b>0.0319</b>	0.0547	0.0591

A coefficient from the Henderson and Pabis model,  $a$ , depends on the shape of the sample (Gigler et al. 2000b). The obtained  $a$ -values from all five temperatures were observed to be not significantly different ( $SD = 0.07$ ). This result corresponds to the present study's assumption that at each temperature, the size and shape distribution of the samples used were fairly uniform. Hence, the Henderson and Pabis model best predicted the drying rate of forest residues at all studied air temperature ranges (Fig. 3). The relationship between the drying constant,  $k$  ( $\text{min}^{-1}$ ) and the drying air temperature,  $T$  ( $^{\circ}\text{C}$ )

was expressed as a second order regression equation with a coefficient of determination ( $R^2$ ) of 0.99. A similar type of correlation was developed for Pistachio nut (Midilli and Kucuk 2003) and flax fibers (Ghazanfari et al. 2006b).

$$k = -3 * 10^{-5} T^2 + 0.004 T - 0.104 \quad (7)$$



**Figure 4.** Drying constant ( $k$ ) of forest residues plotting with drying temperatures (Henderson and Pabis model)

## CONCLUSIONS

Pine forest residues primarily consist of tops, braches, small stems, leaves, and needles left after logging operations; they are potential sources of biomass for energy applications, if they can be properly dried, transported, and stored without any decay. Pine forest residues after chipping can be fractionated into clean chips (51%), branches (19%), bark (13%), leaves (9%), and small particles (8%) and had fairly uniform chemical and fuel properties. Thin layer drying of forest residues at various drying air temperatures was conducted to evaluate the drying rate and mechanism of drying forest residues. The Henderson and Pabis equation was found to best fit with the experimental drying data at all drying air temperatures, indicating that diffusion was the dominating drying mechanism for forest residues. The drying constant,  $k$  indicated that drying of forest residues can be faster at high air temperatures. A correlation between the  $k$  value and drying air temperature was developed in the form of a second order regression equation. The predicted thin layer drying model will be useful in designing a low cost deep bed dryer for forest residues.

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## NOMENCLATURE

$MR$	= Dimensionless moisture ratio
$M_o$	= Initial moisture content (% db)
$M$	= Instantaneous moisture content after a time $t$ (% db)
$M_e$	= Equilibrium moisture content (% db)
$k$	= Experimental determined drying constant ( $\text{min}^{-1}$ )
$t$	= Drying time (min)
$a$	= Henderson & Pabis constant (Depends on particle shape)
$n$	= Page's constant (exponent)
$N$	= The number of observations
$n_p$	= The number of constants in any drying model
$R^2$	= Coefficient of determination
$RMSE$	= Root mean square error
$\chi^2$	= Chi-square
$HHV$	= Higher heating value (MJ/kg)
$T$	= Drying air temperature ( $^{\circ}\text{C}$ )
$C_1, C_2, C_3$ & $C_4$	= Constants

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