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RESEARCH ARTICLE

Drying Kinetics and Mathematical Modeling of Casuarina Equisetifolia Wood Chips at Various Temperatures

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Abstract

Casuarina equisetifolia wood is extensively used as fire wood and is also being used extensively in gassifiers. Drying is an important procedure which has to be carried out before the wood is burnt. Experiments on Casuarina wood chips of dimension 5.08 cm × 5.08 cm with 2.54 cm thickness were carried out between 80°C to 100°C in a tray drier using air flow velocity of 0.5m/s. Initial moisture content was found to be 48% on dry basis. The experimental drying curves showed only the falling rate period. Eleven thin-layer drying kinetic models were fitted with the experimental drying kinetics values and individual model constants were found. These models were compared using statistical measures like correlation coefficient, root mean square error, mean bias error and reduced chi-square to estimate the best model that would fit for the experiment. The drying rate and effective diffusion coefficient (D_{eff}) were found to increase with temperature.

Keywords

Casuarina, Thin-layer drying models, Tray drier, Statistical measures, Effective diffusion coefficient

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1 Introduction

Casuarina equisetifolia also known as beef wood is an evergreen tree that yields hard and dense wood and is naturally found on subtropical and tropical coastlines of Australia and many other Asian countries like Malaysia, Polynesia and Vanuatu [1]. From many decades this species has been extensively introduced in many parts of the world including India, Bangladesh, China, Middle East, Africa, America and many other places [2–4]. The colour of the heartwood varies from pale red-brown to dark red brown. Casuarina wood can be potentially used for direct combustion, gasification and many other purposes. Its wood ignites readily even when green, and ashes retain heat for long periods. Along with this, the rapid growth of tree makesthis tree known as the best firewood and also its wood produces high-quality charcoal. Calorific value of a matured Casuarina species can give about 20.20 $MJkg^{-1}$ [5]. This wood can be used both industrially and domestically. However, fresh wood is difficult to collect, transport and use, due to very high moisture content, low energy content and low bulk density [6, 7].

Dry wood results in enhanced efficiency, elevated combustion flame temperature, decreased gaseous emissions and reduced fuel use [8]. Drying of any wood removes the watercontent and thus its weight is reduced easing the shipping and handling costs. Apart from this there will be an increase in wood's strength properties [9].

Mathematical modelling is a method to have set of equations that can describe the system at any instant. The solution of the model must predict the process parameters based on initial conditions at a given time [10–12]. Initial moisture, morphology, dimensions, temperature, pressure, humidity, type of thermal energy used (infrared, microwave, hot air, etc) will effect the drying kinetics and final product quality [13–15]. The facts on the moisture removal process during the drying operation and fitting these information into mathematical models will be helpful for the design and the operation of the driers of both large scale and small scale and hence is important to improve the performance of the driers [16–18]. Laboratory based modelling may help to portray the thin layer drying process of Casuarina wood chips, as large scale studies are both expensive and time consuming [19, 20]. Many works on drying of biomass have been carried out, most of them being on agricultural crops, fruits and vegetables. Not much literature on drying kinetics and mathematical modelling of Casuarina are available. The main aim of this work is to experimentally determine the drying rate kinetics of the wood chips, fit the experimental data into the drying mathematical models, determine the constants of each model used and to predict the best model using statistical analysis. Effective diffusion coefficient, which explains the moisture removal process were also found at different temperatures. By using this data, activation energy was calculated.

2 Experimental

2.1 Materials

Freshly felled Casuarina equisetifolia lumbers were procured from the outskirts of Bangalore region. The barks were segregated and only the fresh wood were cut into 5.08×5.08 cm and 2.54 cm thick cuboids and were sealed in a polythene bag and stored in a freezer at 4°C, until the experiments were performed.

2.2 Experimental set-up

Laboratory scale tray drier (UniversalLab Product Co., India) was used for the drying experiment. The dimensions of the drier were 90 cm (height), 60 cm (depth) and 60 cm (wide). Capacity of the drier was 12 L with 5 kW heating load. The drier consists of a fan, which blows air at a constant velocity of 0.5 m/s. Desired temperature was attained with ±5°C variation. A mesh tray was specially fabricated with thin steel wires, with its opening size 5.08 cm by 5.08 cm separately so that the above mentioned sized wood chip would perfectly be seated on, allowing the drying to take place from all the sides. The fabricated mesh was placed in the middle row of the dryer and the wood chip was placed on it. During the drying process, the weights of the chips were measured using a electronic weighing balance; Shimadzu BL-320H, having an accuracy of ±0.001 g. Dry forceps were used while transferring wood chips from drier to weigh balance.

2.3 Experimental procedure

The wood chips were weighed using an electronic balance. The drying experiments were conducted at 80°C, 90°C and 100°C temperatures with ±2°C variations. The drier was preheated to the required temperature at the start, for half an hour before every experiment was conducted. The chip was weighed and then again placed in the tray drier. The weight of the wood was measured at regular intervals of one hour. Sample was picked out using dry forceps and was weighed and put back very quickly into the drier. All these weighing process was finished within 10 seconds. This process was done for eight hours and later the temperature was increased to 103°C±2°C and left for a day to determine the initial moisture content. Moisture content (MC) and drying rates were calculated at different time and temperatures. The equation to find the moisture content on dry basis is shown in (1). The drying rate was calculated as moisture removed per area of the substance to be dried for a given time interval is shown in Eq. (2) [21]. All experiments were conducted in three sets. The average of these values was used for the statistical examinations and determination of the effective diffusion coefficient.

$$\mathrm{MC} = \frac{\left(\text{wieght of wet wood chip} - \text{weight of dry wood chip}\right)}{\text{weight of dry wood chip}} \tag{1}$$

$$\text{Drying rate} = \frac{\text{kg moisture}}{\left(\text{Area}\right)\left(\text{time}\right)} \tag{2}$$

3 Mathematical Modelling of Drying Curves

Equation (3) is used to calculate the moisture ratio (MR). Where, M_o is initial moisture content (dry basis), M_e is equilibrium moisture content and M_t is the moisture content at a given time on the dry basis.

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

Fluctuations in the relative humidity of the drying air due to the variations in the air flow velocity, temperature, and humid conditions can be observed. However, since the equilibrium moisture content is not high for agricultural products, the above equation is simplified to $MR=M_t/M_o$ [22, 23].

Mathematical models used in the current work are shown in Table 1. These thin layer models can be classified into three groups: theoretical, semi-theoretical and empirical. Theoretical models are based on diffusion equation or simultaneous heat and mass transfer and account for only internal resistance of the moisture movement to the surface. Whereas, semi-theoretical models are based on the closely estimated theoretical equation and empirical depends on the experimental data. Semi-theoretical models are only valid within a given temperature, relative humidity, airflow velocity and moisture content range for which they are developed [24, 25]. Empirical models describe the drying curve for the conditions of the experiments but they neglect fundamentals of the drying process and their parameters have no physical meaning [26, 27]. These two model types deem only the external resistance to moisture movement [28, 29]. Lewis, Page, Modified Page, Henderson and Pabis, Logarithmic, two term, modified Henderson and Pabis, simplified Fick's diffusion and modified Page-II were the semi-theoretical models and Wang and Singh, Thomson were the empirical models used in this paper. Regression analysis were performed and the models were chosen to be the best if the value of correlation coefficient (R^2) is high (nearer to one) and Chi-square (χ^2), Root Mean Square Error (RMSE), Mean Bias Error (MBE) values are minimum [24, 30]. The formulasz of the above mentioned statistical measures are shown below

$$R^2 = \frac{\sum_{i=1}^{N}\left(MR_i - MR_{pre,i}\right).\sum_{i=1}^{N}\left(MR_i - MR_{exp,i}\right)}{\sqrt{\left[\sum_{i=1}^{N}(MR_i - MR_{pre,i}{}^2)\right].\left[\sum_{i=1}^{N}\left(MR_i - MRexp,i\right)^2\right]}} \tag{4}$$

$$RMSE = [\frac{1}{N}\sum_{i=1}^{N}(MR_{pre,i} - MR_{exp,i})^2]^{1/2} \quad (5)$$

$$\chi^2 = \frac{\sum_{i=1}^{N}(MR_{exp,i} - MR_{pre,i})^2}{N - n} \quad (6)$$

$$MBE = \frac{1}{N}\sum_{i=1}^{N}(MR_{pre,i} - MR_{exp,i}) \quad (7)$$

Here, N is the total number of observations, n is the number of model parameters, MR denotes the moisture ratio; $MR_{pre,i}$ and $MR_{exp,i}$ is the predicted and experimental moisture ratio at i^{th} observation respectively.

4 Results and Discussion

4.1 Drying characteristics of the Casuarina chips

The initial moisture content of the wood was found to be around 48% on dry basis. Moisture content was decreased with increase in time and temperature (Fig. 1). The drying time was reduced to attain determined moisture content as the temperature is increased. This may be attributed to the increase in the water molecule energy due to an increase in the temperature and also because of a larger difference in the partial pressure of the vapor in the drying air to the vapor pressure of the moisture in the wood at higher temperatures [31, 32] which consequences in quicker evaporation of moisture from the wood chips. Similar observations may be made from Fig. 2. Constant drying rate period was not observed and all the drying was found only in the falling rate period (Fig. 3). Absence of constant rate period may be due to the absence of free surface water, therefore no surface evaporation took place at constant rate. Hence we can infer that mass transfer of the moisture during drying took place predominantly by liquid diffusion. Similar results have been obtained from other authors [22, 33, 34]. From Fig. 3, it is clear that the drying rate was found to be higher at high temperature and decreased with increase in drying time.

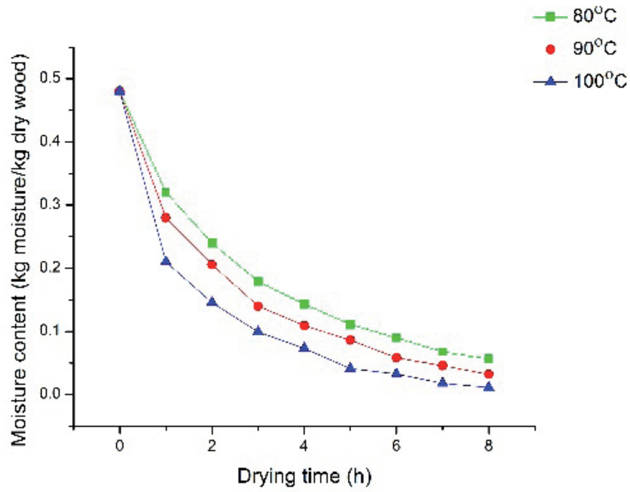

Fig. 1 Variation of moisture content with time for different temperatures

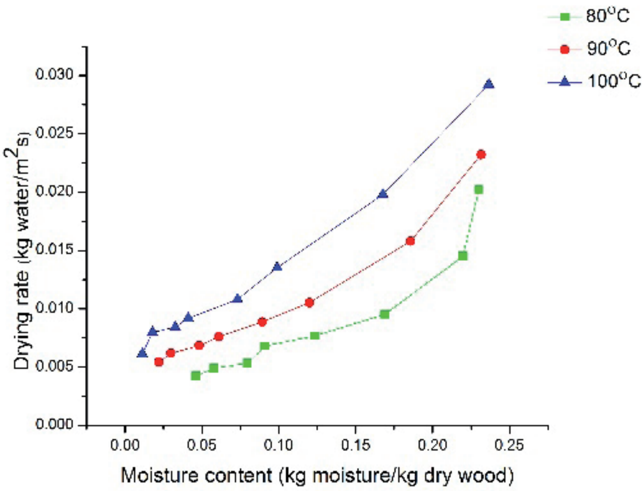

Fig. 2 Variation of drying rate with moisture content at different temperatures

Table 1 Various mathematical models used

Model no.	Model name	Model equation	Name of the model
1	Lewis	$MR = e^{-kt}$	Lewis (1921)
2	Page	$MR = e^{-kt^n}$	Page (1949)
3	Modified Page	$MR = e^{-(kt)^n}$	Wang and Singh (1978)
4	Henderson and Pabis	$MR = ae^{-kt}$	Henderson and Pabis (1969)
5	Logarithmic	$MR = ae^{-kt} + c$	Yagcıoglu et al. (1999)
6	Two term	$MR = ae^{-k_o t} + be^{-k_1 t}$	Henderson (1974)
7	Wang and Singh	$MR = 1 + at + bt^2$	Wang and Singh (1978)
8	Thomson	$t = a. \ln MR + b. [\ln(MR)]^2$	Thompson et al. (1968)
9	Modified Henderson and Pabis	$MR=ae^{-kt} + be^{-gt} + ce^{-ht}$	Karathanos (1999)
10	Simplified Fick's Diffusion	$MR = ae^{\frac{-ct}{L^2}}$	Diamente and Munro (1991)
11	Modified Page-II	$MR = e^{-k\left(\frac{t}{L^2}\right)^n}$	Diamente and Munro (1993)

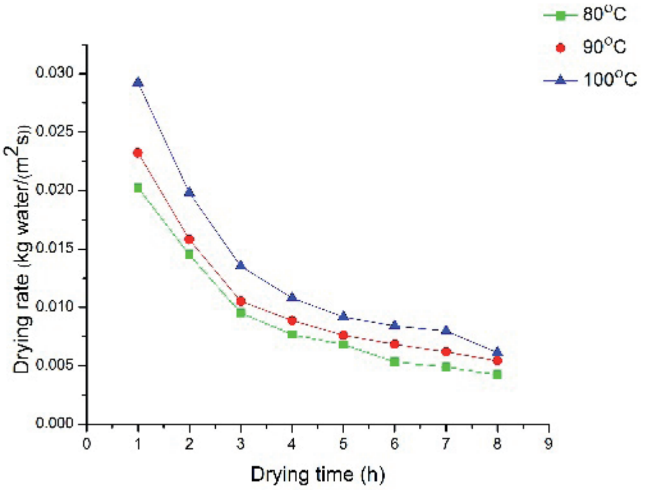

Fig. 3 Variation of drying rate with drying time at different temperatures

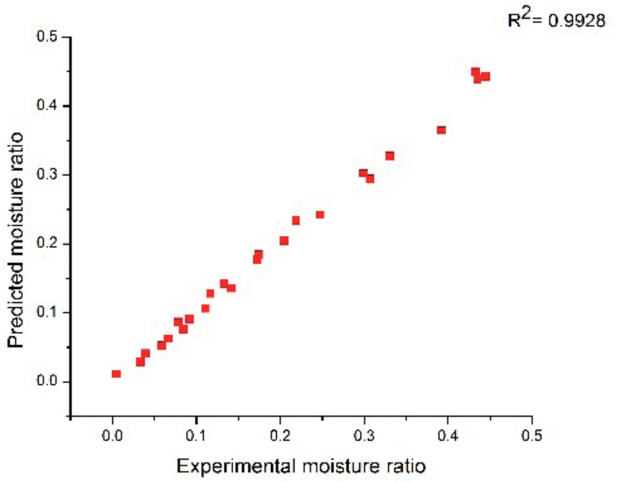

Fig. 4 Experimental versus predicted moisture ratio (Modified Henderson and Pabis model) for different drying temperatures

4.2 Mathematical modeling

The experimental data of the drying process were fit into the mathematical models as listed in Table 1, which are frequently used in the drying of biomass feed stock [29, 35–41]. These were fitted to the experimental drying facts to find the constants of each model. The closeness of the relation of the model was determined by the correlation coefficient (R^2). χ^2 and RMSE shows the deviation between the experimental and predicted values. In particular, lower the χ^2 value; better the fit and lower RMSE shows good short term performance. MBE provides information on the long term performance of the correlations, helping for the comparisons of the actual deviation between experimental and predicted values [42, 43].

Various constants and the regression analysis data calculated for eleven models at various temperatures (T) are shown in Table 2. All the models used were found to predict drying to a good extent, however modified Henderson and Pabis, and Logarithmic model was found to predict the drying very well as it showed R^2 values nearly approaching to one, χ^2 and RMSE values almost approach zero. Fig. 4 and Fig. 5, shows the plot of predicted and experimental moisture ratio to illustrate the very good performance of the modified Henderson and Pabis model and the logarithmic model respectively. The performance of the logarithmic model and modified Henderson and Pabis model showed a straight line with R^2 0.9958 and 0.9928 respectively, showing that these models are highly suitable for predicting the drying characteristics of Casuarina wood chips in the conducted experimental range of this study.

4.3 Effective diffusion coefficient (D_{eff}) and activation energy

Fick's second law equation is used to determine the diffusivity of water in the falling rate period, assuming diffusivity to be the sole physical mechanism responsible for the transfer of water to the wood surface [44–46]. In other words, during the falling rate period only the internal resistance regulates the mass transfer of

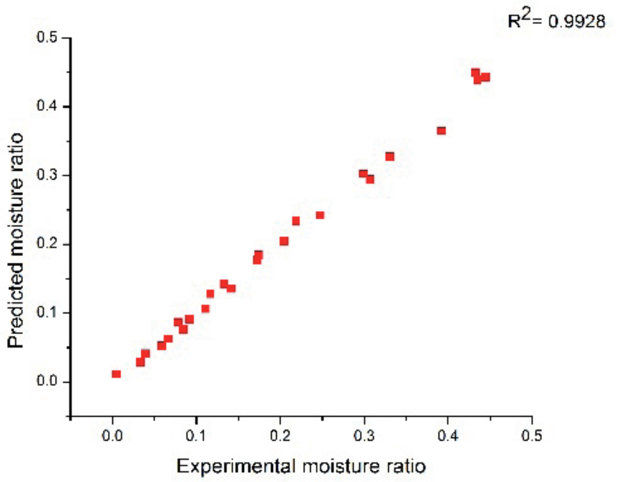

Fig. 5 Experimental versus predicted moisture ratio (Logarithmic model) for different drying temperatures

the moisture. Relation between the moisture ratio and the effective diffusion coefficient was given by Crank (1975) [47] and this could be used for slab geometry by making an assumption that initial moisture is uniformly distributed in the sample. This relation was reduced to Eq. (8) for long term drying [12, 48–50]. In order to use (8), it is assumed that the wood chip is homogeneous, isotropic, drying occurs only in the falling rate period, mass transfer through the wood is controlled by liquid diffusion and any effect caused by shrinkage is negligible [40, 51].

$$MR = \frac{8}{\pi^2}\exp\left[\frac{-\pi^2 D_{eff} t}{4L^2}\right] \qquad (8)$$

Where L is the half thickness of the wood chip (m), D_{eff} is the effective diffusion coefficient in m^2/s and t is the drying time in seconds. By plotting Ln MR versus drying time, D_{eff} can be found from the slope of the line (Fig. 6). D_{eff} increased with increase in temperature from $4.43\times10^{-9} m^2/s$to 10.15×10^{-9} m^2/s as the movement of water to the surface of the wood chip increases, the values are tabulated in Table 3.

Table 2 Statistical analysis coefficients of various models used

Model	T °C	Model Constants	R^2	RMSE	χ^2	MBE
Lewis	80 90 100	k=0.335 k=0.412 k=0.549	0.962 0.984 0.993	0.11204 0.09075 0.15198	0.014420 0.009452 0.026441	0.061051 0.048502 0.134409
Page	80 90 100	K=0.7060 n=0.554 K=0.7246 n=0.654 K=0.7490 n=0.827	0.940 0.976 0.978	0.03013 0.02091 0.00802	0.001037 0.000494 0.000730	0.023407 0.002373 0.005135
Modified Page	80 90 100	K=0.5592 n=0.554 K=0.6428 n=0.654 K=0.6565 n=0.827	0.950 0.983 0.993	0.09718 0.08740 0.08610	0.010791 0.008736 0.008472	0.029271 0.043381 0.060662
Henderson and Pabis	80 90 100	K=0.236 a=0.5767 K=0.3149 a=0.6070 K=0.4103 a=0.6760	0.982 0.997 0.996	0.16363 0.00736 0.00936	0.003064 6.5×10^{-5} 9.8×10^{-5}	0.000896 0.000970 0.002188
Logarithmic	80 90 100	a=0.6320 k=0.1731 c=-0.08186 a=0.6146 k=0.2746 c=-0.02746 a=0.6698 k=0.3505 c=-0.02922	0.986 0.998 0.999	0.01458 0.00541 0.00540	2.4×10^{-5} 3.25×10^{-5} 3.36×10^{-5}	5.5×10^{-5} 2.62×10^{-5} 1.35×10^{-6}
Two-Term	80 90 100	a=0.3145 b=0.2622 k_o=0.2326 k_1=0.2326 a=0.344 b=0.2630 k_o=0.3149 k_1=0.3149 a=0.2137 b=0.1495 k_o=0.4139 k_1=0.4139	0.983 0.997 0.996	0.01637 0.00728 0.09915	0.000311 6.05×10^{-5} 0.011238	0.000896 0.000976 0.072836
Wang and Singh	80 90 100	a=-0.616 b=0.088 a=-0.626 b=0.092 a=-0.627 b=0.096	0.978 0.973 0.963	0.71876 0.78311 0.87752	0.590418 0.070095 0.880065	0.313887 0.341463 0.394958
Thompson	80 90 100	a=-1.133 b=0.314 a=-0.822 b=0.711 a=-1.588 b=0.548	0.973 0.931 0.980	0.02420 0.19210 0.07564	0.000669 0.042117 0.006539	0.004219 0.165853 0.023169
Modified Henderson and Pabis	80 90 100	a=0.2142 k=0.2326 b=0.1903 g=0.2326 c=0.1750 h=0.2326 a=0.2332 k=0.3149 b=0.1976 g=0.3149 c=0.1761 h=0.3149 a=0.2718 k=0.4103 b=0.2170 g=0.4103 c=0.1872 h=0.4103	0.982 0.996 0.996	0.01636 0.00727 0.00929	0.000306 6.05×10^{-5} 9.87×10^{-5}	0.000896 0.000976 0.002188
Simplified Fick's diffusion equation (SFFD)	80 90 100	a=1.6753 c=0.403 a=1.5431 c=0.542 a=1.0597 c=0.902	0.980 0.995 0.974	0.46668 0.32798 0.47155	0.217790 0.122293 0.254125	0.405107 0.262663 0.332878
Modified Page equation-II	80 90 100	k=1.0586 n=0.554 k=1.02326 n=0.654 k=1.04707 n=0.827	0.929 0.976 0.978	0.04869 0.02088 0.02531	0.002709 0.000498 0.000732	0.036099 0.002214 0.004852

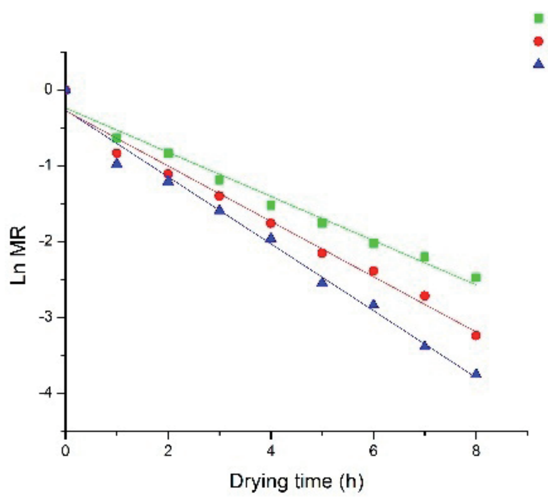

Fig. 6 Plot of ln MR vs drying time at various temperatures.

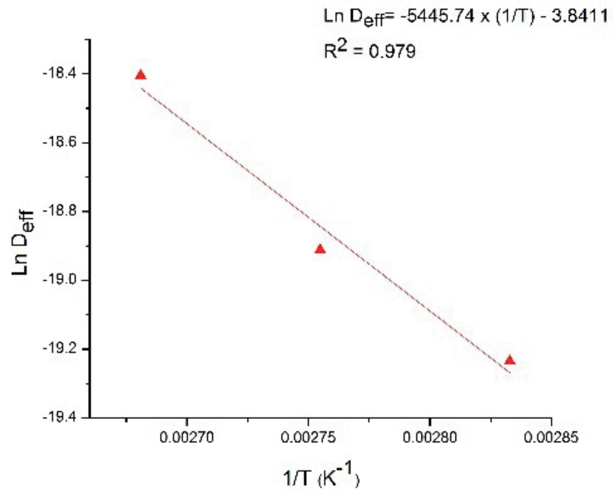

Fig. 7 Relation between the reciprocal of absolute temperature and effective diffusion coefficient

The activation energy was estimated using the Arrhenius equation shown in Eq. (9) [51–54]. Ln D_{eff} versus reciprocal of absolute drying air temperature (T_a) were plotted (Fig. 7) and from the slope of the line, activation energy (kJ/mol) and from the intercept pre-exponential factor was found.

$$D_{eff} = D_o exp\left[\frac{-E_a}{RT_a}\right] \tag{9}$$

Table 3 Effective diffusivities at different temperatures

Drying air Temperature (°C)	Effective diffusion coefficient (m^2/s)	R^2
80	4.43×10^{-9}	0.992
90	6.12×10^{-9}	0.993
100	10.15×10^{-9}	0.996

In the above equation D_{eff} is the effective diffusion coefficient in m^2/s, D_o is the pre-exponential factor of the Arrhenius equation in m^2/s, E_a is the activation energy in kJ/molK and T_a is absolute drying air temperature in K. Activation Energy was found to be 45.27 kJ/molK and the pre-exponential factor was determined as 2.15×10^{-2} m^2/s.

5 Conclusions

Initial moisture content of the Casuarina wood chips was found to be approximately 48% on dry basis. Constant rate drying period was not observed. The results showed that drying curves were greatly influenced by the drying temperature. The drying rate was found to increase with drying temperature. Logarithmic and Modified Henderson and Pabis models predicted the drying rate in a best manner among the models used in the temperature rage 80°C to 100°C. The effective diffusion coefficient increased from 4.43×10^{-9} m^2/sto 10.15×10^{-9} m^2/s as the temperature increased from 80°C to 100°C. The activation energy for the water diffusion was found to be 45.27 kJ/mol K and pre-exponential factor was determined to be 2.15×10^{-2} m^2/s.

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