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Isothermal Drying Kinetic of Sengon Wood (Paraserianthes Falcataria) Using Combined Infrared and Hotair: Experimental and Modeling Study

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Abstract

Sengon wood beams are widely used as a wood packaging material. According to the International Standards for Phytosanitary Measures (ISPM), wood packaging materials must be pests-free. One method for eliminating problems with wood is by heat treatment or drying. This research aims to determine the kinetics of isothermal drying of sengon wood blocks using a combination of infrared and hot air heating. The drying process is carried out at temperatures of 70, 80 and 90 °C, air velocity of 1, 2 and 3 m/s until the final moisture content of the wood reaches 19%. The experimental data were fitted to four drying models, and analyzed using non-linear regression to determine the most suitable model and evaluated through the coefficient of determination (R^2), chi-square (X^2), and root mean square error (RMSE). The research results revealed that the temperature of the wood core reached 56 ^{o}C the fastest at a temperature of 90 ^{o}C and an air velocity of 3 m/s in 45 minutes. The highest R^2 coefficient 0.9998 is found on the model page at a drying temperature of 70°C and an air velocity of 3 m/s with the lowest X, RMSE values of 0.00001 and 0.0025 respectively. The effective moisture diffusivity of sengon wood particles increased from 1.80×10^{-6} to 2.47×10^{-6} m^2/min due to the increase in temperature treatment from 70 to 90 °C. The largest diffusion activation energy at an air velocity of 3 m/s is 23.92 kJ/mol.

Keywords: sengon wood, infrared and hot air, drying kinetics model, effective moisture diffusivity, activation energy.

1. Introduction

Sengon wood (Paraserianthesfalcataria) is Indonesia's most important multipurpose pioneer species. It is one of the types of industrial forest plantations in Indonesia[1]. Sengon wood is widely used wood packaging materials such as pallets, crates, and barrels. Wood packaging materials are susceptible to pests and plant diseases[2]. To reduce this risk, The International Plant Protection Convention (IPPC) applies the International Standard Phytosanitary Measure No.15 (ISPM No.15)[3], where the core temperature of the wood must reach a minimum temperature of 56 oC and the moisture content is below 20%[4][5].

The heat treatment process usually begins with a drying process which reduces the moisture content of the wood. The drying process that is commonly used is using hot air during conventional drying. In addition, infrared rays can be used in the process of drying wood. Kollmann etal. used infrared radiation for the first time to dry spruce and beech wood in 1967. They found that the surface temperature of spruce wood increased faster than that of beech wood, due to the spruce wood has the lowest density[6].

Straže et al. compared the drying time using infrared light (IR) with hot air (HA) at 90 oC, where infrared radiation produces a faster drying time compared to hot air.[7].Infrared dryer combined with hot air reported by Hany S. EL-Mesery et al. where a minimum specific energy consumption (SEC) of 3.8 MJ/kg was recorded using an infrared hot air convection (IR-HA) combined drying system, which is at 60oCand the airvelocity is 0.5 m/s the condition optimum for efficient drying of biomass with high moisture content[8].

Drying kinetics is a complex phenomenon and requires reliable models to predict drying behavior. There are few papers related to mathematical modelling of wood drying. Brys et al. Drying spruce, beech, willow, and alder sawdust, higher drying air temperatures and air flow velocity result in lower drying times and higher drying rates[9]. Hosseinabadi et al. the effective moisture diffusivity and activation energy of poplar wood particles increases due to increases in temperature and air velocity[10]. The performance of the logarithmic and the modified Henderson and Pabis model was very suitable for predicting the drying characteristics of Spruce wood chips[11].

Drying sengon wood using a combined infrared dryer and hot air has never been done before. This study aims to obtain a mathematical kinetic model that describes the drying characteristics of sengon wood beams with an initial moisture content of 35-40% dry basis during isothermal drying. The experiment carried out at 70, 80 and 90^{o}C with variations in air velocity of 1, 2 and 3 m/s. This study limited the drying time when the core wood temperature reached minimum 56 ^{o}C

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evenly distributed in all wood profilesand wood moisture content below 20% according to the ISPM standard.

2. Experimental

2.1. Material

Sengon wood has just been felled with an estimated age of about five years, it was cut into blocks measuring 300 mm long, 50 mm wide, and 100 mm high, according to ISO 6780 2003[12], stored in an airtight container before testing.The number of wooden beam samples used in this research was 9 pieces

2.2. Experiment Equipment

Laboratory dryer with internal dimensions of length 60 cm, width 60 cm, and height 60 cm,The infrared heater halogen type 500 W with an intensity of 0.5 W/cm^{-2} and a wavelength of 1.5 to 8 µm and electric heater tubular type 500 W. The hot airis blown into the dryer using blower equipped with a valve to control the velocity of air (Figure1). Temperature measurements using a 12-channel Lutron BTM-4208SD temperature recorder with a type K thermocouple temperature sensor for measuring the decrease in wood mass using an Arduino ADC HX 711 digital scale.

2.3. Experimentalprocedure

Experiments were carried out at the Heat Transfer and Thermodynamics Laboratory, Department of Mechanical Engineering, SebelasMaret University, Solo, Indonesia. Firstly, the Sengon wood beams were dried in the sun for about two days until their moisture content reached around 35-40%, which was measured by a moisture meter brand Benetech GM620, after that they were placed in an airtight container for testing.Infrared heaters and hot air are used simultaneously to obtain the required drying room temperature, temperature control using a temperature controller Autonics brand and a K type thermocouple temperature sensor. The test is carried out at a temperature of 70, 80and 90^{o}C,air velocity at 1, 2and 3 m/s.Wood core temperature measurements were carried out at three points to determine the uniformity of wood temperature (Figure 2). Measurements of temperature and reduction in wood mass were carried out at intervals of 15 minutes untilwood moisture content 19 %. Samples of wood beams subjected to final heat treatment were in the oven at ± 103 ^{o}C for 24 hours to obtain the equilibrium moisture content[13]. The moisture content of wood is known after the drying process is carried out[14].The wood moisture content is the amount of water contained in the wood relative to its dry weight expressed as a percentage, and it is calculated using[15][16].

$$MC = \frac{W_h - W_o}{W_o} x100\% \tag{1}$$

Where MC is the wood's moisture content, W_h is the wet wood's mass, and W_o is the mass of dry wood. The drying rate of wood is obtained by comparing the change in wood weight that occurs with the duration of the drying process. The drying rate can be calculated using the following equation[17].

$$DR = \frac{M_c - M_{i+t}}{\Delta t} \tag{2}$$

WhereDR is the drying rate, $M_c$is the initial moisture content, M_{i+t} is the moisture content at time t, and Δt is the drying time interval.

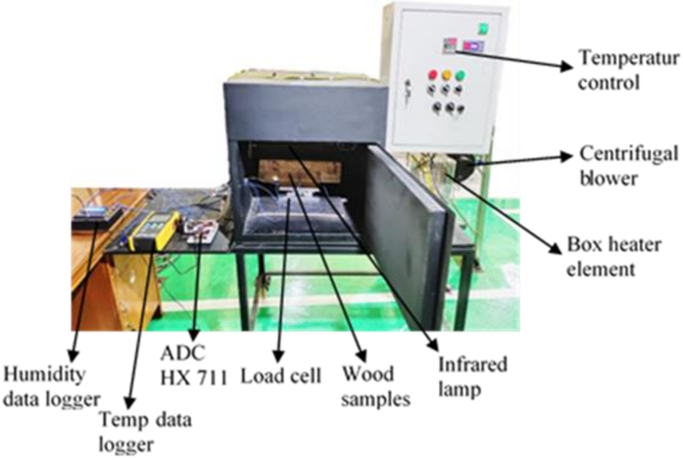

Figure 1. Experimental equipment used in the infrared-hot air drying

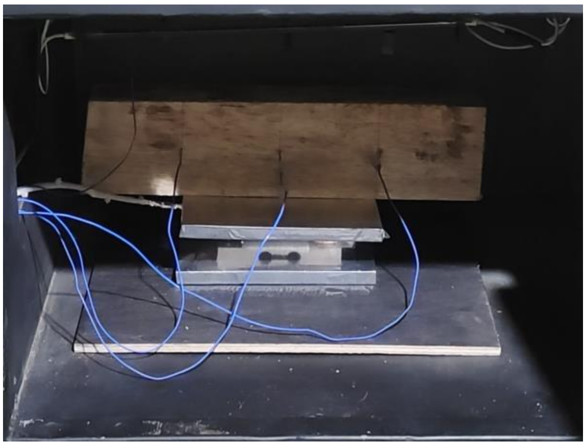

Figure 2. Installation of a thermocouple for measuring wood core temperature

In drying, diffusivity is used to indicate the flow of the moisture content material. In the falling rate period, the reduction in moisture content is controlled mainly by molecular diffusion. The effective diffusivity coefficient is determined by adjusting the mathematical model for fluid diffusion according to the Second Fick Law by assuming a slab geometry. The moisture content only migrates by diffusion, ignoring volumetric shrinkage, constant temperature, and long drying times[18][19].

$$\frac{\partial \mathrm{M}}{\partial \mathrm{t}} = \mathrm{D_{eff}}.\nabla^2.\mathrm{M} \tag{3}$$

$$MR = \frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)}\exp\left(-\frac{(2n+1)^2.\pi^2.\mathrm{D_{eff}}.t}{4L^2}\right) \tag{4}$$

For a long drying time, it can be simplified to:

$$\mathrm{MR} = \frac{8}{\pi^2}\exp\left(-\frac{\pi^2.\mathrm{D_{eff}}.t}{4L^2}\right) \tag{5}$$

$$ln\mathrm{MR} = \ln\left(\frac{8}{\pi^2}\right) - \left(\frac{\pi^2.\mathrm{D_{eff}}}{4L^2}\right).t \tag{6}$$

From equation (7), the effective diffusivity can be calculated by plotting ln(MR) against drying time (t). This gives a straight line with a certain slope so that the D_{eff} value is obtained, which can be expressed as[20]:

$$Slope = \frac{\pi^2.\mathrm{D_{eff}}}{4L^2} \tag{7}$$

D_{eff} is the effective moisture diffusivity, t is the drying time, and L is the half thickness of the sengon wood.

3. Mathematical Modeling

Moisture ratio (MR) decreased during the drying process. The experimental moisture ratio of sengon wood at different initial moisture content at time (t) was computed as the following equation[17].

$$\mathrm{MR} = \frac{\mathrm{M_t} - \mathrm{M_e}}{\mathrm{M_o} - \mathrm{M_e}} \tag{8}$$

MR is the moisture ratio, M_t is the moisture content at a specific time, M_e is the equilibrium moisture content, and M_o is the initial moisture content.The experimental infrared and hot air dryer data for sengon wood were fitted into four drying models. The mathematical models used to determine the drying kinetics of sengon wood are the Newton, Page, Henderson &Pabis and Wang & Singh models. These four models represent semi-theoretical and empirical models in this research, which are represented in Table 1.

Table 1. The mathematical models used for isothermal drying of sengon wood

No	Model name	Isothermal dryingmodelequation	Parameter
1	Newtons	MR = exp(-kt)	k
2	Page	MR = exp(-kt^n)	k, n
3	Henderson&Pabis	MR = aexp (-kt)	a, k
4	Wang&Sing	MR = at^2 + bt + 1	a,b

The validity test was carried out using the Coefficient of Determination (R^2) criteria, chi-square (X^2), and Root Mean Square Error (RMSE). The R^2 value indicates the ability of the model with the highest value, 1. The value X^2 is the difference between the distribution of the calculated data and the distribution of the test data. Whereasthe RMSE indicates the deviation between the calculated results and the measured dataand its value is close to zero. The greater the value of R^2 the smaller of X^2 and RMSE, the better the model used. The values of R^2, X^2, RMSE, is calculated by the following equations[21][22].

$$\mathrm{R}^2 = 1 - \left[\frac{\sum_{i=1}^{n}\left(\mathrm{MR_{pre,i}} - \mathrm{MR_{exp,i}}\right)^2}{\sum_{i=1}^{n}\left(\overline{\mathrm{MR}}_{\mathrm{pre,i}} - \mathrm{MR_{exp,i}}\right)^2}\right] \tag{9}$$

$$\chi^2 = \frac{\sum_{i=1}^{n}\left(\mathrm{MR_{pre,i}} - \mathrm{MR_{exp,i}}\right)^2}{\mathrm{N} - \mathrm{z}} \tag{10}$$

$$R\mathrm{MSE} = \sqrt{\frac{\sum_{i=1}^{n}\left(\mathrm{MR_{pre,i}} - \mathrm{MR_{exp,i}}\right)^2}{\mathrm{n}}} \tag{11}$$

Where N is the number of observation data, z is the number of mathematical model constants. $MR_{pre,i}$and $MR_{exp,i,}$ respectively, are the predicted and experimental moisture ratios in the i-observation[23].

4. Results and Discussion

The sengon wood beams used in the study had an average moisture content of 36.78% on a dry basis. The temperature profile of sengon wood core is shown in Figure 3. The fastest drying time occurs at 90°C with an air velocity of 3m/s with a core wood temperature of 61.75 °C, and the longest drying time occurs at a temperature of 70°C at an air velocity1 m/s, the wood core temperature of 58.3°C. Higher drying temperature and air velocity result in faster core temperature reaching 56 °C[8]. The increase in temperature at the start of drying is faster because it is associated with an increase in the energy of the water molecules due to the increase in temperature and also because of a more significant difference between the partial pressure of the vapor in the drying air and the pressure of the water vapor in the wood. Asghari et al. In high relative humidity the latent heat transfer will reduce,so the temperature drop will be less in[24][25].

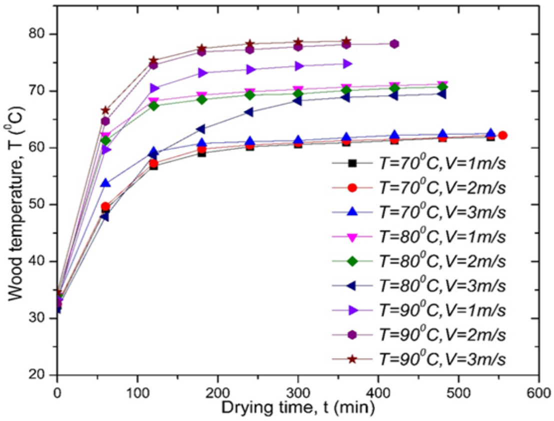

Figure 3. The temperature profile of sengon wood during the drying process

The water content and drying rate decrease with drying time as can be seen (Figures 4 and 5). Drying temperature plays an important role in the drying process. It can be observed that the higher the air temperature, the shorter the drying time and the higher the drying rate.The fastest reduction in moisture content was obtained at a temperature of 90 °C and an air velocity of 3 m/s which took 330 minutes.Meanwhile, the longest time to reach a final moisture content of 19% was at a temperature of 70 °C and an air velocity of 2 m/s with a time of 550 minutes.A decrease in drying time and an increase in drying rate with increasing drying temperature have been observed for sawdust of spruce, beech, willow, alder[9]. and drying of poplar wood particles[10].

4.1. Mathematical Modeling

The kinetics modeling of sengon wood drying uses four different models. The data from the test results are entered into a non-linear mathematical model. The results of the statistical analysis and the estimated parameter values for this model are listed in Table 2. The closeness of the model relationship is determined by the correlation coefficient (R^2), X^2, and RMSE, which indicates the deviation between the experimental and predicted values. The greater the value of R^2 and the smaller the value of X^2, RMSE, the better the method used[26]. The results show that the four models fit the experimental data well. Based on the coefficient of determination (R^2) value, the Page and Newton model gives the highest R^2 value andX^2, the lowest RMSE among other models.

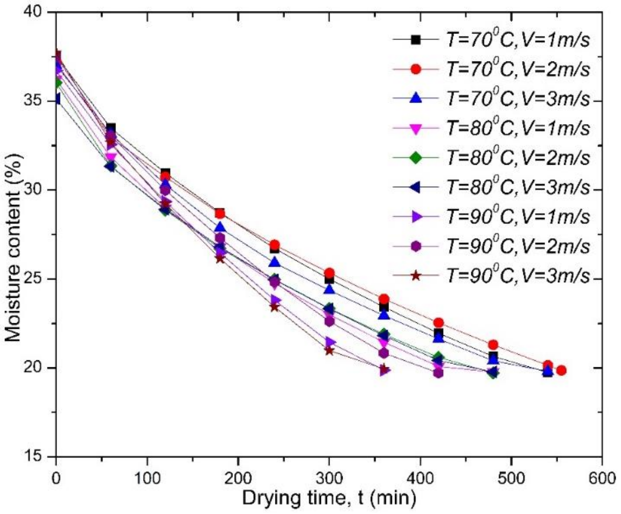

Figure 4. Decrease in moisture content of sengon wood

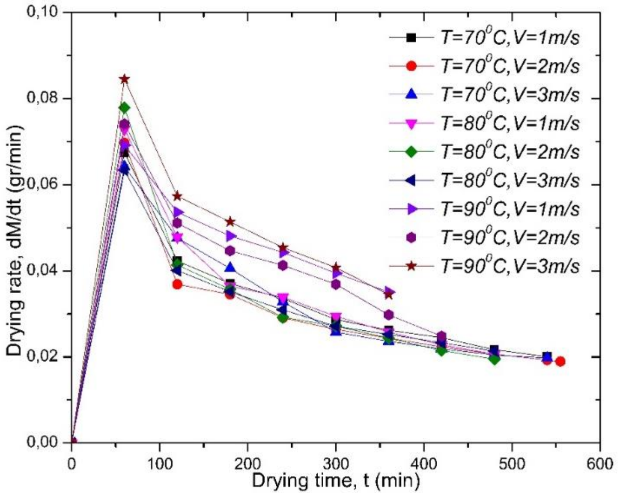

Figure 5. Sengon wood drying rate profile during the treatment process

Table 2. Results of statistical analysis for the four kinetic models of drying sengon wood at different temperatures and air velocities

Drying Condition		**Model**	**Model Parameter**	**R^2**	**RMSE**	**χ2**
T, °C	**u, m/s**					
70	1	Newton	k=0,0019	0,9971	0,1097	0,0003
		Page	k=0,0044, n=0,8622	0,9993	0,0049	0,00004
		Henderson&Pabis	a=0,0319, k=0,0018	0,9966	0,2162	0,0030
		Wang&Singh	a=0,0018, b=1E-6	0,9943	0,0511	0,0009
70	2	Newton	k=0,0018	0,9949	0,0766	0,0005
		Page	k=0,00655, n=0,7442	0,9984	0,0028	0,00008
		Henderson&Pabis	a=0,0454, k=0,0017	0,9943	0,2242	0,0037
		Wang &Singh	a=0,0017, b=1E-6	0,9935	0,0645	0,0007
70	3	Newton	k=0,0019	0,9946	0,1257	0,0006
		Page	k=0,00438, n=0,8641	0,9998	0,0025	0,00001
		Henderson&Pabis	a=0,0425, k=0,0018	0,9936	0,2402	0,0046
		Wang &Singh	a=0,002, b=2E-6	0,9884	0,2175	0,0042
80	1	Newton	k=0,0022	0,9955	0,1005	0,0004
		Page	k=0,00548, n=0,8434	0,9997	0,0067	0,00002
		Henderson&Pabis	a=0,0392, k=0,0021	0,9948	0,2183	0,0034
		Wang &Singh	a=0,0022, b=2E-6	0,9965	0,1360	0,0006
80	2	Newton	k=0,0021	0,9906	0,0979	0,0007
		Page	k=0,00762, n=0,776	0,9991	0,0057	0,00004
		Henderson&Pabis	a=0,0566, k=0,0019	0,9886	0,2693	0,0076
		Wang -Singh	a=0,0021, b=2E-6	0,9922	0,1768	0,0016
80	3	Newton	k=0,002	0,9970	0,0937	0,0003
		Page	k=0,0045, n=0,8614	0,9992	0,0051	0,00004
		Henderson&Pabis	a=0,0285, k=0,0019	0,9966	0,2017	0,0023
		Wang&Singh	a=0,0019, b=2E-6	0,9878	0,2541	0,0076
90	1	Newton	k=0,0026	0,9993	0,0500	0,00005
		Page	k=0,00261, n=1,0011	0,9993	0,0084	0,00005
		Henderson&Pabis	a=0,0073, k=0,0027	0,9991	0,1074	0,0002
		Wang&Singh	a=0,0024, b=2E-6	0,9994	0,0826	0,0001
90	2	Newton	k=0,0025	0,9992	0,0286	0,00008
		Page	k=0,00372, n=0,927	0,9994	0,0029	0,00003
		Henderson&Pabis	a=0,013, k=0,0024	0,9991	0,1340	0,0005
		Wang&Singh	a=0,0023, b=2E-6	0,9988	0,1209	0,0004
90	3	Newton	k=0,0029	0,9992	0,0618	0,00006
		Page	k=0,00394, n=0,9453	0,9991	0,0095	0,00006
		Henderson&Pabis	a=0,0051, k=0,0029	0,9992	0,0841	0,0001
		Wang&Singh	a=0,0027, b=3E-6	0,9975	0,1353	0,0014

Figure 6 shows the relationship between drying time and moisture ratio (MR), those obtained from experimental tests and calculated by the four selected models at the temperature of 70 °C and air velocity of 3 m/s. It can be seen from the graph that the Page and Newton model are closer to the experimental results compared to the Henderson-Pabisand the wang-Singh model. The resulting graphic pads stay away from the experimental results. The performance of the Page model shows a straight line with R^2, X^2 and RMSE of 0.9998, 0.00001 and 0.0025 respectively, this shows that the Page model is very suitable for predicting the drying characteristics of sengon wood with the treatment method used in this study

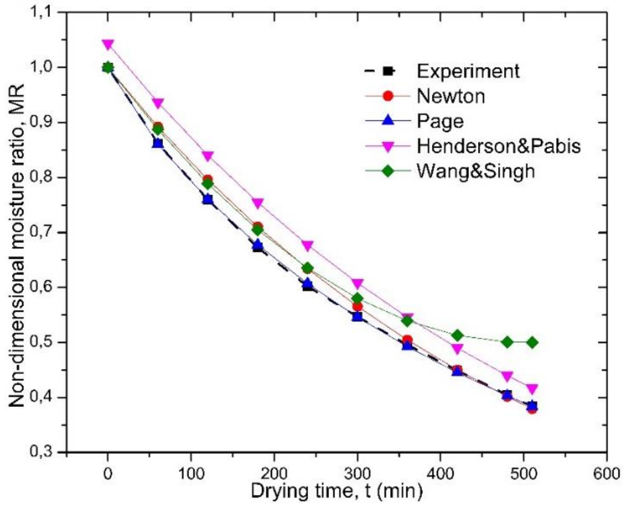

Figure 6. Experimental moisture ratio vs. moisture ratio at 70°C at an air velocity of 3 m/s

4.2. Effective diffusion coefficient (Deff) and activation energy

Table 3 presents the values of effective diffusivity coefficient (D_{eff}) that are calculated from Equation 7 for all treatments. Wood drying generally occurs during the falling rate period, and water transfer during this period is controlled by internal diffusion. This period was analyzed to understand the drying kinetics by determining the effective diffusivity coefficient (D_{eff}).[11]. The diffusivity of water from the sengon wood will increase with increasing temperature. However, the tendency of other factors can also affect the diffusivity of a material, such as surface area, thickness, air velocity, RH, drying time, and other factors.The effective diffusivity coefficient for drying sengon wood for treatment at 70, 80 and 90 °C is in the range $1.8x10^{-6}$to $2.5x10^{-6}$ m^2/min with increasing treatment temperature, the value of the effective diffusivity coefficient also increases[10][27].

Table 3. Effective diffusivity at different temperature

Air velocity (m/s)	Temperature (°C)	D_{eff} (m^2/min)
1	70	1,79854E-06
2		
3		
1	80	1,99555E-06
2		
3		
1	90	2,47085E-06
2		
3		

Activation energy is the minimum energy required to initiate the diffusion of water from a material[28][29]. The diffusion activation energy in drying sengon wood can be estimated by the Arrhenius equation[11][20][30][31].

$$D = D_o \exp\left[-\frac{E_a}{RT_a}\right] \quad (12)$$

$$k_i = \frac{E_a}{R} \quad (13)$$

Where Ea is the activation energy (kJ/mol), Do is the pre-exponential factor (m^2/s), R is the ideal gas constant (8.314 J./mol.K), and T is the absolute temperature (K). The activation energy (Ea) can be determined by finding the slope of the straight-line (k_i) is presented in Figure 7[10][32].

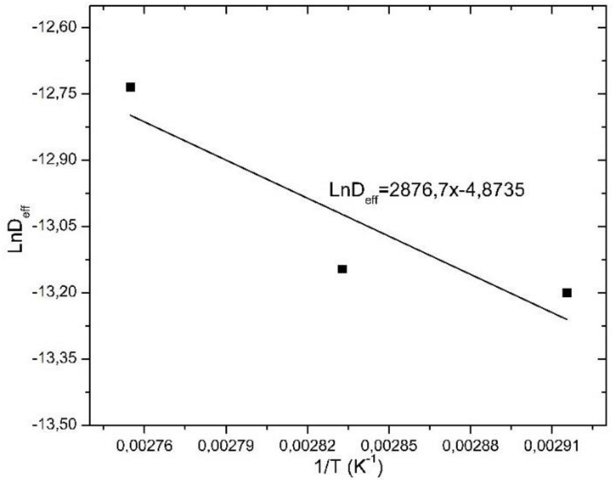

Figure 7. Relation between the reciprocal of absolute temperature and effective diffusion coefficient at air velocity of 3 m/s

Table 4. Activation energy at different air velocity

Temperature (°C)	Air velocity (m/s)	Activation energy (Ea) (kJ/mol)
70	1	19,23
80		
90		
70	2	19,57
80		
90		
70	3	23,92
80		
90		

Table 4. present the values of activation energy in drying sengon wood at temperatures of 70, 80 and 90°C, air velocity of 1, 2, and 3 m/s is in the range 19.23 to 23.92kJ/mol. With increasing air velocity, the value of the activation energy coefficient also increases.Not different from the measurements carried out by Nadhariet al.[26] that the activation energy of acacia magium wood is 41.07 kJ/mol. Sridhar and Madhu[11]. stated that the activation energy of Casuarina Wood Chips is kJ/mol and Hosseinabadi et al the activation energy of poplar wood particlesfor 1 m/s and 1.5 m/s air flow velocities were calculated as 27.8 kJ/mol and 50.8 kJ/mol , respectively[10].

5. Conclusion

Sengon wood with an average initial moisture content of 36.78 % on a dry basis is subjected to a drying process to obtain a minimum wood core temperature of 56 °C and a final moisture content of 19 % using an infrared-hot air drying at temperatures of 70, 80 and 90 °C with an air velocity of 1, 2 and 3 m/s, the most optimal conditions at a treatment temperature of 90 °C with an air velocity of 3 m/s, a drying time of 330 minutes and a temperature of 70 °C, an air velocity of 2 m/s is the minimum condition with a treatment duration of 555 minutes. The Page model is the most suitable model to describe the drying characteristics of sengon wood dried at all temperatures and air velocity. The highest R^2 coefficient of

0.99086 is found in the Page model with a drying temperature of 70°C, air velocity of 3 m/s with the lowest X^2 and RMSE values of 0.00001 and 0.0025 respectively. The effective diffusivity coefficient for drying sengon wood is in the range of $1.8x10^{-6}$ to $2.5x10^{-6}$ m^2/min. With increasing temperature treatment, the diffusivity coefficient also increases. Increasing the air velocityalso increases the activation energy in the drying process of sengon wood, the activation energy value is in the range of 19.23 to 23.92 kJ/mol.

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