International Journal of Thermal Technologies
ISSN 2277 - 4114

Research Article

Determination of the diffusion coefficient and the activation energy of water desorption in IROKO wood (Chlorophora excelsa), during a conductive drying

Monkam Louis[a,b], Ayina Ohandja Louis Max[a,] Chugoua Njamen Adeline[b] and Mekongo Ateba Florent[b]

[a]Doctorate School of Physics and Engineering Sciences – University of Douala Cameroun– B.P. 8698 DOUALA - CAMEROUN.
[b]Energy Laboratory of the Doctorate School of Physics and Engineering Sciences – University of Douala Cameroun– B.P. 8698 DOUALA - CAMEROUN.

Accepted 15August 2013, Available online 01 Sept. 2013, **Vol.3, No.3 (Sept. 2013)**

Abstract

Five temperatures steps 40, 45, 50, 60 and 70 ° C in an approach that is both experimental and analytical helped the study of the kinetic drying of Iroko wood in calm atmosphere. Increasing the temperature significantly reduces drying time and shows a high absorption of water by heated air. The reduced moisture content of tropical biomaterial is evaluated, the model of Lahsasni, M.Kouhila Mr. Mahrouz and Kechaou is established in correlation with experimental points for subsequent exploitation, the solution of Fick's second equation, allowed us to determine the diffusion coefficient of water in these experimental conditions whose values ranges from 1.66741x10-6 to 2.5924 x 10-6 x 10-6 (m2.s-1) depending on the applied temperatures. We also estimated the activation energy of water (20.23877 kJ / mol) during drying by analyzing the Arrhenius relation.

Keywords: *Iroko - drying kinetics - diffusion coefficient - activation energy - modeling - reduced moisture content - approximation.*

Introduction

The importance of wood in economic activity or in bioclimatic habitat is not an issue of doubt nowadays. Some species such as Iroko, the Sappelli, Moabi, Doussié and many others are highly produced and marketed in the Congo Basin. Wood has versatile uses such as heating, cooking, furniture, insulation, construction, papermaking and toys, sculpture and decoration, the realization of bridges, stairs and flooring etc.

The use of wood is strongly encouraged in the current context of the environment, and the goal of the research is to make it a material of the future. Its better implementation requires development of new processes and an understanding of its properties to reduce waste. The choice of Iroko in this work is motivated by its various uses and the fact that drying is a process that involves independent variables or parameters (conductivity and diffusivity, diffusion coefficient, moisture content, activation energy, desorption and many others), which contribute to the characterization of natural resource development, optimization and use of wood species in both crafts in the processing industry, in the enrichment of the literature of tropical wood, modeling of drying processes, controlling deformations and damage due to dimensional variations.

A large number of works has been done both in the theoretical and experimental characterizations (Hebderson S.M.1971; Lahsasni (2002) ; Midilli (2002)) of wood species in temperate regions. Initiatives for tropical wood has also been undertaken such as the works of M.SIMO TAGNE *et al* (2011), J.L NSOUANDELE *et al* (2010) which considers even the diffusion coefficient of water. But we note that the work in determining this coefficient is made on the basis of three levels of temperature. It is very insufficient for us to cover the drying domain with medium temperature if the need for extrapolation arises, and the fact that the diffusion coefficient of water in the wood depends on the drying temperature. In this work, an experimental study represented by drying curves was performed for temperatures of 40° C, 45° C, 50° C, 60° C and 70° C. The model of Lahsasni et (2002) with six parameters, has a better correlation of the experimental points for the determination of the searched diffusion coefficient. A comparative study of the results obtained with those encountered in the current literature of wood drying has helped to identify and appreciate the later.

2. Experimental Analyses

2.1 Experimental Protocol

The experimental setup is shown in figure 1. Figure 2 and 3 show wood samples of Chlorophora excels and an electronic balance.

Corresponding author: Monkam Louis

Fig 1 Experimental dryer (IUT of excelsa)

Fig 2 Wood sample of (Chlorophora excels)

Fig 3 Electronic balance for weighing samples

2.2 Representation of the kinetic model.

Four drying models were tested to describe the variation of the reduced moisture content versus time (A. Lopez *et al*., 2000; Lahsasni (2002). (table 1). The reduced moisture content (RM) is determined by the relation:

$$MR = \frac{M - Me}{M_0 - Me} \quad (1)$$

To measure water loss from samples, we used the dryer shown in Figure 1. It is an oven with; six resistive heating elements, a thermostat with adjustable temperature, in which the sample with dimensions (10x5x2cm) figure 2 are placed on small wooden pallets favoring air circulation.

To obtain initially the anhydrous mass of the sample, we weigh and measure its dimensions, and then proceeds to its drying at 103° C and we regularly weigh at least for 48 hours until constant mass in attained. The remaining sample is weighed regularly by an electronic balance with accuracy of about 0.1 g after each removal without replacement and with variable time increases. The process is repeated for jumps in temperature of 40° C, 45° C, 50° C, 60° C and 70° C.

Me is the mass of the sample at equilibrium depending on the temperature and the activity of the water in the wood. Following the works of Piamente L.M *et al*. (1993), Togrul. I.T *et al* (2002), equation (1) is approximated by the following expression:

$$MR = \frac{M}{M_0} \quad (1)$$

Table1 Mathematical model of the tested drying

Model name	**Expression**
Midilli-Kucuk	MR = a.exp(-ktn)+b.t
Logarithmic behaviour	MR = a.exp(-kt)+c
Lahsasni, MKouhila, M. Mahrouz *et al* Kechaou	MR = a.exp(-kt)+b.exp (-gt)+c.exp(-ht)
Henderson	MR = a.exp(-kt)+b.exp(-k1t)

M_0 is the initial mass and M the instantaneous mass of the sample.

The criterion for evaluating the quality of the smoothing parameter is adopted statistical (chi-square) formula:

$$\chi^2 = \frac{\sum_{i=1}^{n}\left(MR_{i,\exp} - MR_{i,cal}\right)^2}{N - n} \quad (3)$$

N is the number of measurements and n the number of parameters to be determined in the approximate function.

The mathematical model which has a very low value of x^2 (Chi-square) is chosen as the best to describe the drying evolution. In this work, the model of Lahsasni *et al.* (2002), is established; the parameters are summarized in Table 2.

The parameter x^2 is of the order of 2.10^{-4} in average and thus shows a better agreement with the experimental data.

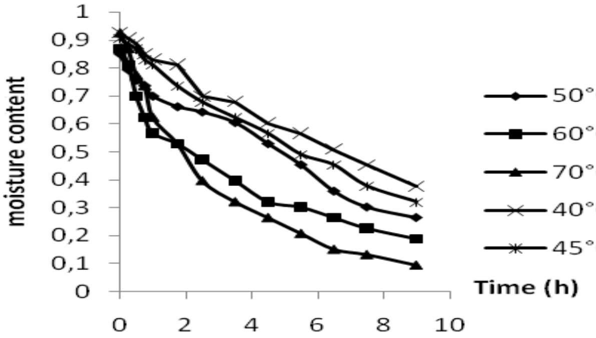

Fig 4 Experimental curves of the reduced moisture content as a function of time

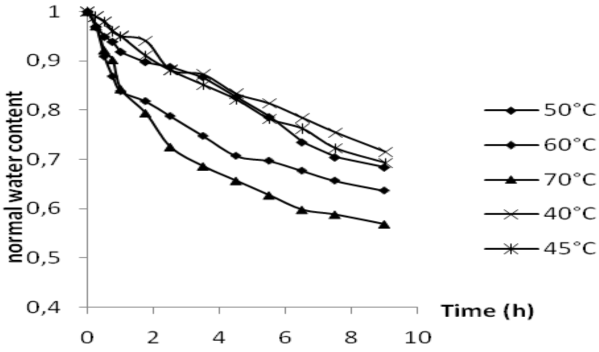

Fig 5 Experimental curves of the normal reduced moisture content as a function of time

Table 2 Coefficients of the approximation function

Model	T (°C)	Coefficients						
		a	k	c	b	g	h	χ^2
Lahsasni, M.Kouhila, M. Mahrouz *et al* Kechaou	40	0,0007	2,29	0,029	0,971	0,034	0,614	0,000095
	45	-0,01	2,29	0,053	0,956	0,036	0,613	0,000028
	50	1,054	0,155	-0,68	0,202	0,6	0,015	0,0003489
	60	0,127	1,568	0,072	0,518	0,808	0,027	0,0001807
	70	-0,02	2,305	0,701	0,024	0,324	0,598	0,0001031

3. Results and interpretation

3.1 Presentation of results

The drying process of wood is to assess its hygroscopic nature which indicates the affinity that the material may have with its environment. Moisture transfer between the air and the wood is shown by curves that describe the evolution of the moisture of the dry base Figure 4 or reduced moisture content in Figure 5. Figures 6 to 10 reconsiders the experimental reduced moisture content and calculated to present the convenience. We may observe a good match between the two results. Figure 11 allows us to observe the evolution of the drying speeds according to the applied temperatures. We may see that the temperature has a certain effect on the drying as seen from the divergence between the curves although it converges around 50% for the reduced moisture content. We also note that below 50°C the rate of drying is relatively low and will cause a long drying time which would be advantageously true for lower temperatures, such as natural drying.

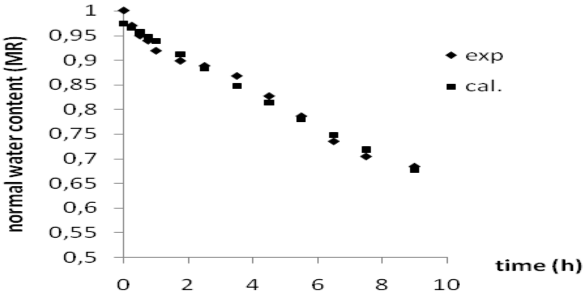

Fig 6 Theoretical and experimental curves at 50 ° C

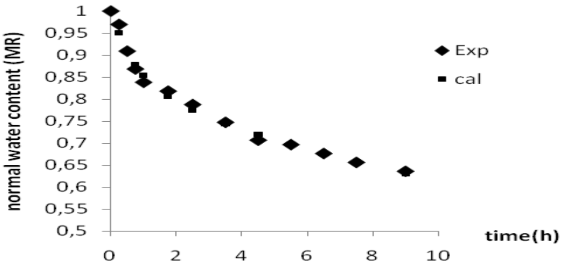

Fig 7 Theoretical and experimental curves at 60 ° C

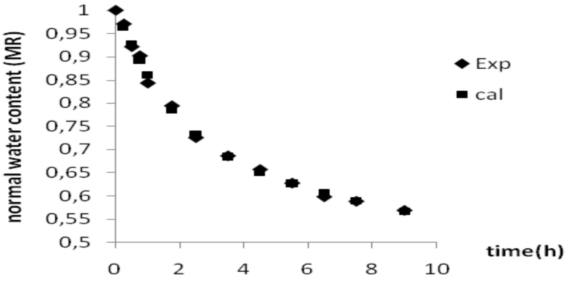

Fig 8 Theoretical and experimental curves at 70 ° C

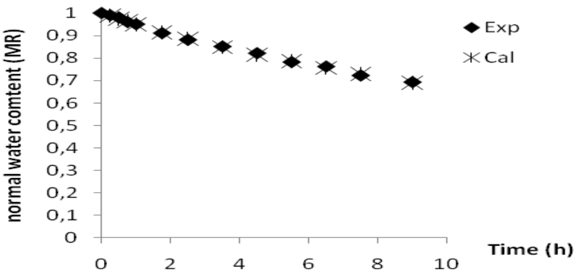

Fig 9 Theoretical and experimental curves at 45 ° C

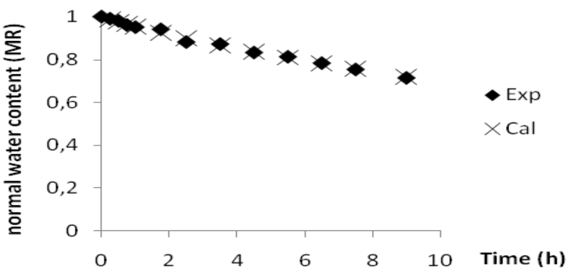

Fig 10 Theoretical and experimental curves at 40°

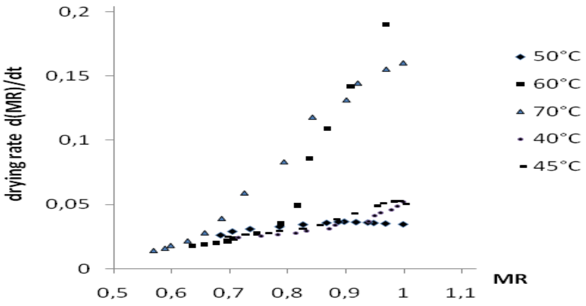

Fig 11 Drying rate as a function of the reduced moisture content

3.2 Diffusion coefficient

The results presented above are used to determine the coefficient of diffusion of water in the wood with the range of temperatures that have served in this measurement.

These experimental results can be treated by the Fick's diffusion equation, whose analytical solution of the second law, in the slab geometry (Perré P. *et al*. 1997) expresses the reduced moisture content by:

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

As hypothesis, the initial moisture distribution is uniform, shrinkage negligible, the external resistance is neglected and the effective diffusion coefficient assumed constant.
L is half the thickness of the sample (m),

$$L = \frac{e}{2}$$

n: Number of limits taken into account. (n = 0, 1, 2, 3 ....).
For sufficiently large periods of drying, the solution of this equation can be simplified to the first term in a series (n = 0). Thus

$$\ln(MR) = \ln\frac{8}{\pi^2} - \frac{\pi^2 D_{eff}\,t}{4L^2} \qquad (5)$$

A linear trend in the representation of
Ln (MR) = f (t) from the experimental data, is a line of slope:

$$P = -\frac{\pi^2 D_{eff}}{4L^2} \qquad (6)$$

This slope (Figure 12) provides measurement of effective diffusion coefficient for each drying temperature as a function of time, and is calculated by substituting the experimental data into equation (6).

The values obtained are reported in Table 3. We note that the diffusion coefficient D_{eff} increases with temperature. Compared to other values found in the literature of wood drying, they are within an acceptable range, taking into account the conditions of temperature, relative humidity, there need also to take into account the nature of the species studied and the assumptions made. Jean Michel Hernandez (1991) built the curve of the coefficient of mass transfer in the diffusive model for the Oak wood and we note that, this coefficient varies between $0,5.10^{-10}$ and 10^{-8} (m^2/ s).

3.3 Activation energy

The diffusion coefficient is related to temperature by the Arrhenius equation (A. Lopez 2000):

$$D_{eff} = D_0 \exp\left(\frac{-E_a}{RT}\right) \qquad (7)$$

Parameters Ea and D_0 are determined experimentally by plotting the curve (Figure 13) of the equation

$$\mathrm{Ln}(D_{eff}) = f\,(1/T). \qquad (8)$$

The slope of the line in Figure 13 allows us to deduce the activation energy of wood by identification:

Ea = 15.162 (kJ / mol) or 842.347 (kJ / kg), the values found in the literature gives 17.605 kJ / mol for Ayous and 78.015 kJ / mol for ebony M.Simo *et al* (2010), we also find data on maritime pine, Ea = 25.92 kJ / mol at 35 and 55° C indicated by LartigueClaire (1987). These results are consistent taking into account the temperatures and relative humidity applied during the measurements.

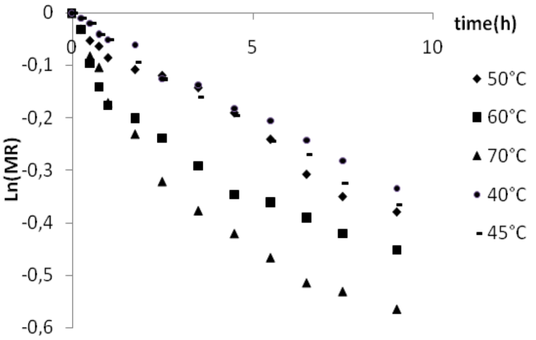

Fig 12 Evolution and logarithmic trend of the reduced moisture content versus time

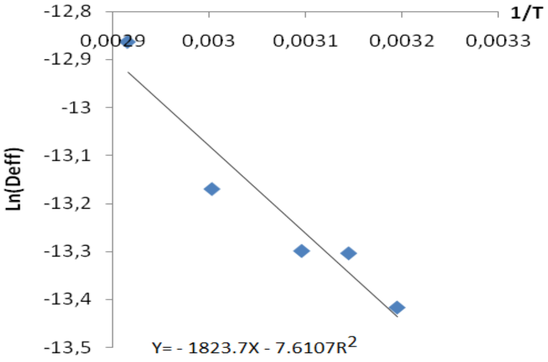

Fig 13 Influence of air temperature on the diffusion coefficient of water

4. Conclusion

Determining the diffusion coefficient and the activation energy of the water in the wood Iroko, constitute a work that characterizes materials. This is an assessment of the affinity of the material with the surrounding environment in terms of water movement, the quantification of the energy needed to lift the water molecules bound to the wall before migration outwardly. These data are necessary in solving mathematical models of drying.

The curves obtained in this work at drying temperatures of 40 ° C, 45 ° C, 50 ° C, 60 ° C and 70 ° C, reflect the transfer of water between the Iroko wood and air. They also show that the temperature has a significant

Table 3 Comparaison des valeurs du coefficient de diffusion

Material, Hr ou ω (%)	T(°C)	Average D_{eff} in permanent regime ($m^2.s^{-1}$)	References
Iroko Hr = 73%	40	1,4889E-06	Present work
	50	1,66741E-06	
	50	1,67552E-06	
	60	1,90677E-06	
	70	2,5924E-06	
Iroko	30	3,65E-12	J.L. Nsouandele *et al*
	40	4,67E-12	
	50	6,24E-12	
Ayous	40	2,055E-9	M. Simo Tagne *et al*
Ebony	40	7,396E-11	M. Simo Tagne *et al*
Hêtre		5,793E-10	Agoua *et al*
Pin Hr = 75%	25	8,878 x 10^{-7}	Perré
Chêne Hr = 75%	25	1,86 x 10^{-7}	Perré
Acajou sec	Free air	2,02 x 10^{-7}	A.Vianou, A.Giradey

impact on the diffusive drying kinetics and indirectly on the thermohydric parameters of the wood. Drying time decreases considerably when the temperature is high. The values of the diffusion coefficient obtained vary from 1.4889 x 10^{-6} to 2.5924 x 10^{-6} (m^2. s-1) and increase gradually as the air temperature rises; this behavior is consistent with that observed by other researchers. The activation energy obtained from the Arrhenius equation has the value 15.162 (kJ / mol), the empirical model Lahsasni *et al* (2002) gave a better fit with the experimental points and has permitted us to established a representation model of curves of normed moisture. However, the discrepancies between our results and those found in the literature may be due to several reasons, including the origins of samples and the conditions of temperature and relative humidity of air in which the sample was exposed.

Nomenclature

Deff: Effective diffusion coefficient (m^2s^{-1})
D0: constant of the Arrhenius equation (m^2s^{-1})
Ea: Activation energy (kJ / mol)
Hr : Relative humidity of the air.
M: mass of the sample (g) at the time t.
Me: Equilibrium moisture content of the material.
Mo : Initial mass of the sample (g).
MR: reduced moisture content of the material
N: Number of observations or measurements.
n: number of constants in the mathematical model used.
R: perfect gas constant (R = 8314.10 to 3 kJ / mol. ° K)
T: absolute temperature (T = 273.13 ° K +)
t: drying time (h).
L: index of half thickness of the sample
cal: calculated value
exp: experimental value

References

Henderson .S.M, (1974) Progress in developing the thin layer drying equation, *ASAE*, N°1: 1167-1168.

J,M, Hernandez, (1991), séchage du chêne :caractérisation, procédés convectif et sous vide. thèse *université de Bordeaux I*

Lahsasni, M.Kouhila, M. Mahrouz and N. Kechaou, (2002), Experimental study and modeling of adsorption and desorption isotherms of prickly pear peel(Opuntia ficus indica), *Journal of food engineering*, .55: 201-207

Lartigue Claire, (1987) Mécanismes élémentaires mis en jeu lors du séchage du Pin maritime; *Thèse de Université de Bordeau I*

A.Lopez, A. Iguaz, A. Esnoz and P. Virseda, (2000), Thin layer drying behavior of vegetable wastes from wholesale market, *Drying technology*, 18: 995-1006.

Midilli. A., Kucuk. H ., Yapar . Z., (2002), A new model for single layer drying, *Drying Technology*, 20: 1503-1513.

J.L. Nsouandele *et al* (2010) Determination of the diffusion coefficient of water in tropical woods. *Phys. Chem. News*

Perré,P., Thiercelin,F. (1997). Détermination de l'humidité du bois par détection directe de rayons- X: Validation de la méthode. Les cahiers scientifiques du bois- Volume 1: pp (149- 158). *Edité par ARBOLOR.*

Piamente L.M, Munro PA, (1993) Mathématical modeling of the thin layer solar drying of sweet potato slices. *Solar Energy* 51: 271-276.

M SIMO TAGNE *et al* (2011), Modelisation of desorption isotherms and estimation of the thermophysic and thermodynamic properties of tropical woods in Cameroon: The case of Ayous and Ebony woods. *Revue des Energies Renouvelables* 14 : 487 – 500

Togrul. I. T., Pehlivan . D, (2002) Mathematical modeling of solar drying of apricots in thin layers, *Journal food Engineering* 55: 209-216