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Experimental Determination of the Global Mass Transfer Coefficients of the Tropical Woods in order to Deduce the Drying Curves at the Lower Temperature

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Abstract

We determine the global mass transfer coefficients of five tropical woods (obeche, iroko, lotofa, sapele and frake) coming from Cameroon. In this effect, drying kinetics using a solar dryer and a conventional dryer are utilized. In addition, comparison is doing between the values obtained and these coming from Chileans tropical woods and temperate. Thus, when the drying kinetics are between 0.25 to 1.5m/s, dry temperature equal to 33.5°C and wet temperature equal to 25°C, global mass transfer coefficients are between $2x10^{-5}$ and $4x10^{-5}$ $kg/(m^2.s)$, for the conventional dryer. These values are conform to these obtained on the Chilean tropical woods and less than these obtained on the temperate woods. In the case of an indirect solar dryer functioning between October and November 2004 at Yaoundé, this coefficient is lower because the wood thickness is almost 24mm in the case of conventional drying and 50mm in the case of solar drying. It is coherent to use the correlation established with the temperate wood and given below where the parameters a_o, b_o, c_o and p should be specific on the tropical woods:

$$\frac{1}{K} = a_o \exp\left(\frac{c_o}{T_a}\right) e + b_o \exp\left(\frac{c_o}{T_a}\right) V^{-p} \exp\left(-\frac{1-\frac{RH}{100}}{X_{fsp}-X_{eq}}\right)$$

Keywords: *Global mass transfer coefficients, Drying kinetics, Tropical woods, Conventional dryer, Solar dryer, Experiment, Modeling, Cameroon.*

1. Introduction

The wood exploitation contributes significantly to the financial expansion of the tropical countries. For the case of Cameroon, the wood is after the petroleum the product most exported in the form of volume and the selling price. Also, the interior marker is satisfied in this sense that wood is used such as wood-engraving and it is always used in the building construction. The Environment Forest Sectorial Program (PSFE) is a tool given by the Cameroon in order to maintenance his forest patrimony and to ratify the international exigencies. It is estimated that the 70% of the volume of wood which enter in the Cameroonian sawmills are lost in the form of wood waste, without forgetter that the middle of the tree is also deserted in the forest [1]. The decree

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n°99/781/PM of the 13th October 1999 imposes an interdiction to export thirteen wood species from Cameroon in the form of rough imber. We can cite by example bubinga, doussié, fromager, illonga, iroko, moabi, padouk, sapele and wengé. Thus, it is an uncontested importance to develop the chemical and thermophysical knowledge wood collected in order to ameliorate theirs methods of conservation such as the conventional and solar drying, then to optimize the maintenance of the forest biologic products.

It is true that the characterization of the wood is most diffused in the literature, but the results are not generalize at all tropical woods because the differences observed at the microscopic scale between temperate and those tropical, and same between the same type of wood [2]. The knowledge of the mass diffusion coefficients of the biological materials permits to estimate their drying times and given the possibilities to optimize consummation of the energy during the drying process and to offer possibilities to multiply the techniques of the drying in the view of the technological valorization of wood. Also, the study of the thermal comfort of the building made in wood is ease. In this paper, we determine experimentally the global mass transfer coefficients of five tropical woods come from Cameroon: ayous, sapele, iroko, lotofa and fraké. This coefficient is determined in the literature on the hêtre, épicéa and coïgue woods [3-6].

2. Material and Methods

2.1. Conventional Drying

Immediately at the end of the drying, we have extracted two samples at 2cm of thickness by species in the length way, each sample is localized at 10cm from each extremity. Afterwards, each sample has been identified, weighing and introduced in the oven regular at 103°C in order to determine, after 24h of drying time, the dried mass of each sample [7]. The averages of the two water content obtained by species permit to have the final water content by species and to deduce the dried mass of each utilized board. For each species, the following relation is utilized to determine the dry mass of the board:

$$X_f = \frac{X_{f1}+X_{f2}}{2} \quad (1)$$

$$M_0 = \frac{100 M_f}{X_f+100} \quad (2)$$

With M_f the last measured mass of the board immediately before extracted in the oven and M_0 the dry mass of the board. Anatomical directions and dimensions of the samples are given in table 1. Figures 1 and 2 below present the dryer and the samples in the dryer. Figure 3 presents the oven utilized to give anhydrous ours samples. Figure 4 presents the dry and wet temperatures utilized.

Fig. 1. Equipment and dryer at the controlled atmosphere

Table 1. Description of the boards samples, conventional drying

Species	Lxlxe (cm)	Annual growth rings	Anatomical direction
Ayous	36.5x11.7x2.5	Flatsawn	Radial
Fraké	43x10.8x2.4	Quartersawn	Tangential
Sapele	43x8.8x2.2	Quartersawn	Tangential
Lotofa	43x7x2.4	Quartersawn	Tangential

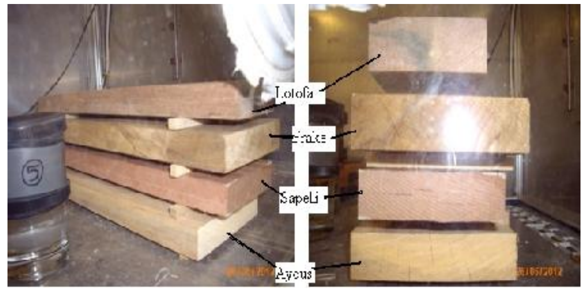


Fig. 2. Disposition of the board during the study of the drying kinetic with constant atmosphere

Fig. 3. Oven utilized

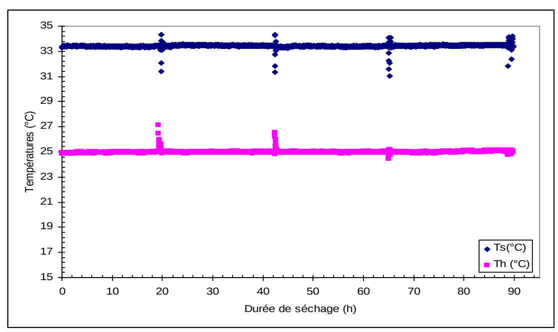


Fig. 4. Dry temperature (T_s) and wet temperature (T_h) utilized during the drying at constant atmosphere

2.2. Solar drying

Solar dryer utilized is presented on the figure 5 below. The walls are made in polyethylene. The dryer is used in the town of Yaoundé-Cameroon from October to November 2004 for the case of ayous and sapele, from November to December 2004 for the case of iroko. Table 2 presents the boards utilized here.

Table 2. Description of the boards samples, solar drying

Species	Lxlxe (cm)	Annual growth rings	Anatomical direction
Ayous	5x35x220	Quartersawn	Tangential
Iroko	5x40x210	Quartersawn	Tangential
Sapele	5x35x220	Quartersawn	Tangential

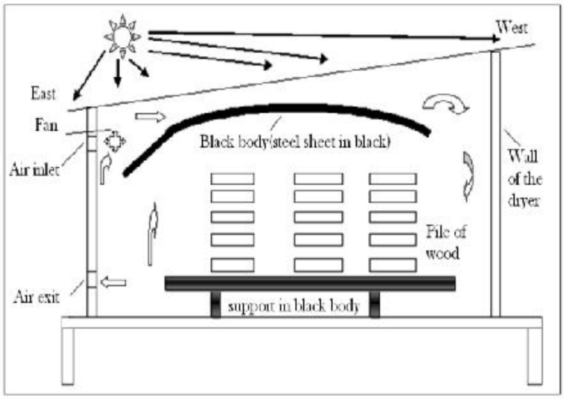


Fig. 5. Indirect solar dryer used. Capacity: 4m^3; air velocity: 1.5m/s

2.3. Methods

We focused to the drying points where the temperature of board becomes constant. When this phase becomes, relation 3 is verified where X is the water content, X_{eq} the equilibrium water content, S the surface of the transfer of humidity, t the drying time, M_o is the dry mass of the board and K the global mass transfer coefficient.

$$-M_0\frac{dX}{dt} = KS(X - X_{eq}) \quad (3)$$

Thus, we suppose that K is constant in the space and in the time, we obtain relation 4 where t_t is the time where the temperature of the board becomes to be constant from the start of the drying, X_t is the water content of the board at the drying time t_t.

$$-LN\left(\frac{X-X_{eq}}{X_t-X_{eq}}\right) = \frac{KS}{M_o}t(h) - \frac{KS}{M_o}t_t(h) \quad (4)$$

Thus, the plot of the function $-LN\left(\frac{X-X_{eq}}{X_t-X_{eq}}\right) = f(t)$ permits to deduce the researched parameter K which is function of the thermophysical conditions of the drying air, in addition of the wood characteristics. When researched parameters are founded, the drying kinetic is plotted using relation 5.

$$X = X_{eq} + (X_t - X_{eq})\exp\left(-\frac{KS}{M_o}(t - t_t)\right) \quad (5)$$

The validation of the correlation is obtained using the square of the correlation coefficient R^2 and the relative difference given by the relation 6.

$$E(\%) = \frac{100}{N}\sum_{i=1}^{N}\frac{|X_{exper_i} - X_{theor_i}|}{X_{exper_i}} \quad (6)$$

Where X_{exper} and X_{theor} are the water content obtained experimentally and by the relation 6 respectively. N is the number of experimental points.

3. Results and Discussion

3.1. Conventional drying

Figure 6 below presents the obtained experimental curves.

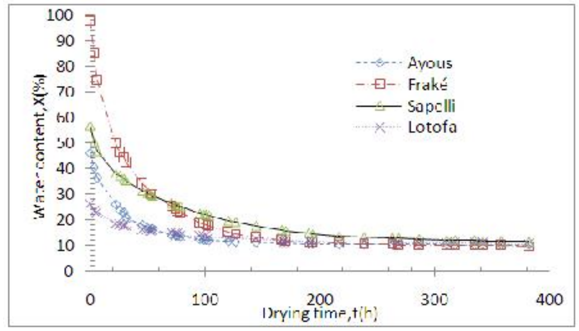
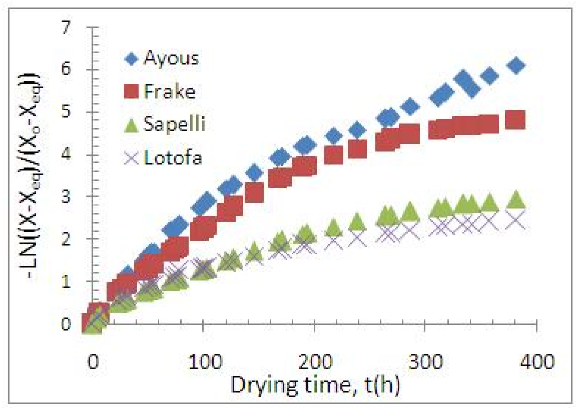
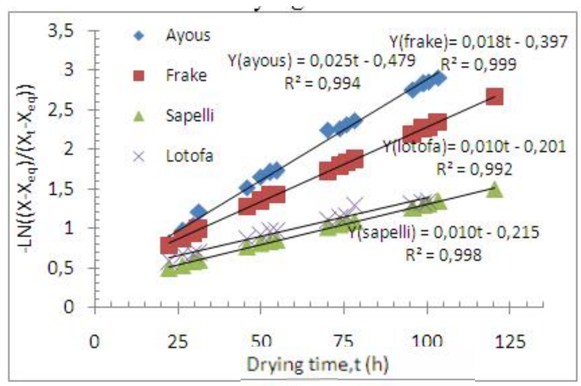


Fig.6. Experimental water content evolutions versus drying time.

The plotting the curve $-LN\left(\frac{X-X_{eq}}{X_t-X_{eq}}\right) = f(t)$ presented at the figure 7 permits to present the transition phase. We have taken the space ranged between 20h and 125h of the drying



(a) Evolution on all drying time



(b) Evolution between 20h and 125h of the drying

Fig.7. $-LN\left(\frac{X-X_{eq}}{X_t-X_{eq}}\right) = f(t)$

Table 3 presents the parameters of ours woods obtained. The relations 7 present the equations obtained with different square of correlation with the values are satisfactory and validate the chosen method.

Table 4 presents the obtained global mass transfer coefficients with the differences when only experimental points after the stabilization of the temperature are confronted (E_1(%)) and when all the drying time is used (E_2(%)).

Table 3. Obtained parameters, Conventional drying

Parameters	Ayous	Lotofa	Sapele	Frake
M_i(g)	696.6	622.73	849.14	1048.25
M_o(g)	475.386	494.575	541.798	530.727
$S_b=2S_{b1}$(cm^2)	854.1	602	746.8	928.8
X_o(%)	45.90	25.91	56.73	97.51
X_t(%)	25.9	18.54	38.13	49.49
X_{eq}(%)	10	10	10	10
X_{first}(%)	12.07	13.43	19.04	14.55

Ayous: $-\ln\left(\frac{X-X_{eq}}{X_t-X_{eq}}\right) = 0.025t(h) - 0.47; R^2 = 0.994$ (7a)

Frake: $-\ln\left(\frac{X-X_{eq}}{X_t-X_{eq}}\right) = 0.018t(h) - 0.3; R^2 = 0.999$ (7b)

Lotofa: $-\ln\left(\frac{X-X_{eq}}{X_t-X_{eq}}\right) = 0.010t(h) - 0.20; R^2 = 0.992$ (7c)

Sapele: $-\ln\left(\frac{X-X_{eq}}{X_t-X_{eq}}\right) = 0.010t(h) - 0.215; R^2 = 0.998$ (7d)

Table 4. Obtained global mass transfers, Conventional drying

Parameters	Ayous	Lotofa	Sapele	Frake
t_t(h)	19.16	20.10	21.50	22.06
K x10^5 (kg/(m^2.s))	3.865	2.282	2.015	2.857
E_1(%)	2.065	2.276	3.308	5.744
E_2(%)	3.272	3.343	4.201	7.126

Table 6. Global mass transfer coefficients and drying conditions of some wood species during conventional drying [4]

Wood Species	e mm	T °C	T_w °C	v m/s	K.10^5 kg/(m^2.s)
Spruce	18	70	50	3	12.5
Spruce	27	70	50	3	7.48
Spruce	41	70	50	3	6.39
Beech	30	70	50	2	5.21
Beech	30	70	50	5	7.81
Coigüe	38	60	44	2.5	0.43

Table 5. Global mass transfer coefficients and drying conditions of the Chilean coigüe *Nothofagus dombeyi* during conventional drying [3]

Cycle	Constants						Variables (Initial Values)				Global Coefficients
	G kg.s^{-1}	e m	S m^2	M_B kg	T_{in} °C	W_{in} kg.kg^{-1}	MC %	W_{out} kg.kg^{-1}	T_{out} °C	T_w °C	K.10^5 kg.m^{-2}.s^{-2}
1	0.3037	0.0184	10.6	50.6	65	0.0359	107.5	0.0359	60	52	3.37
2	0.6116	0.0217	11.5	61.1	64	0.0359	104.1	0.0359	60	17	3.18
3	0.3058	0.0296	12.0	83.3	67	0.0530	107.7	0.0531	58	47	2.06
4	0.6116	0.0308	12.4	87.5	66	0.0474	107.5	0.0474	62	35	1.87

It is clear that experimental points are most defined when wood temperature is stabilized. Additionally, global mass transfer coefficients are higher when the density is lower. It is difficult to connect the duration of the stabilization of wood temperature and the density of ours woods, but it is clear that this duration is localized between 19 and 22h of drying. Tables 5 and 6 show that Chilean tropical wood (coïgue) have the global mass transfer coefficients near of ours studied woods, the drying temperatures used by the authors are almost the double of ours temperatures and the thickness are between 18 and 38mm.

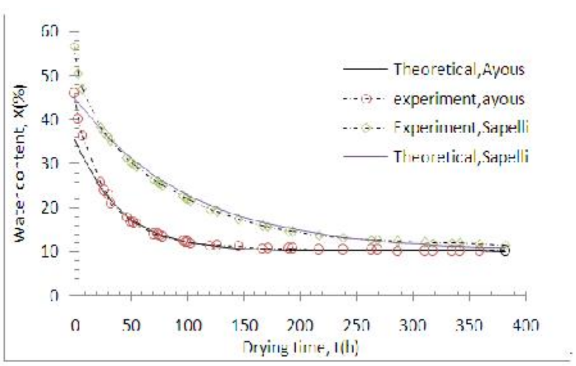


Fig.8. Experimental and theoretical curves of ayous and sapele

It is clear to recall that ours samples have an averaged thickness equal to 24mm. to look at the cycles of the table 5, we constant that the wood thickness has an important influence on the global mass transfer coefficients. Table 6 shows that global mass transfer coefficients of the temperate woods will be superior at the double of those of the tropical woods, showing that the drying of the tropical woods are very lower than temperate woods. Figures 8 and 9 show the evolutions of theoretical and experimental drying kinetics of ours woods. we constant à good representation of the experimental curves after the drying time where the temperature is stabilized, but also after 125h of the drying which is the superior limit used to estimate the global mass transfer coefficients.

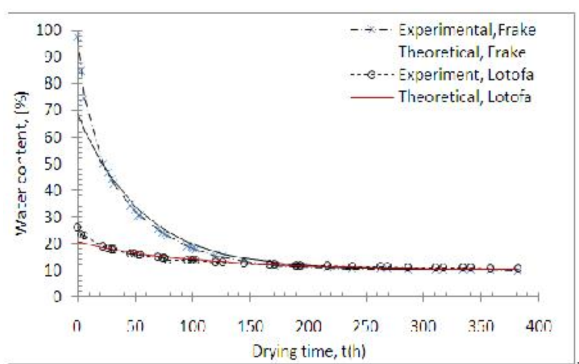


Fig.9. Experimental and theoretical curves of fraké and lotofa

3.2. Solar Drying

In the case of solar drying, the characteristics of the air are function of the day, month and the hour of the day [8,9]. The ones are variables and give irregular variations of the drying kinetic. The view of the experimental curves permit us to distinguish many fragments in the case of ayous and sapele. In the case of iroko only one curve satisfied the description of experimental points. The relations 8, 9 and 10 permit us to traduce experimental kinetics. Squares correlation coefficients values show that this method is adapted. Figures 10, 11 and 12 present the experimental kinetics of the studied woods. It is clear that theoretical curves explained so good experimental curves.

Ayous:

$$t \le 264h,\ -ln\left(\frac{X-X_{eq}}{X_0-X_{eq}}\right) = 0.004t(h)\ , R^2 = 0.993 \quad (8.a)$$

$$t \ge 264h,\ -ln\left(\frac{X-X_{eq}}{X_0-X_{eq}}\right) = 0.013(t(h) - 185.15); R^2 = 0.95 \quad (8.b)$$

Sapele:

$$t \le 360h,\ -ln\left(\frac{X-X_{eq}}{X_0-X_{eq}}\right) = 0.002t(h)\ , R^2 = 0.985 \quad (9.a)$$

$$t \ge 360h,\ -ln\left(\frac{X-X_{eq}}{X_0-X_{eq}}\right) = 0.018(t(h) - 327.17\ , R^2 = 0.913 \quad (9.b)$$

Iroko :

$$\forall t \ge 0; -ln\left(\frac{X-X_{eq}}{X_0-X_{eq}}\right) = 0.006t(h)\ , R^2 = 0.982 \quad (10)$$

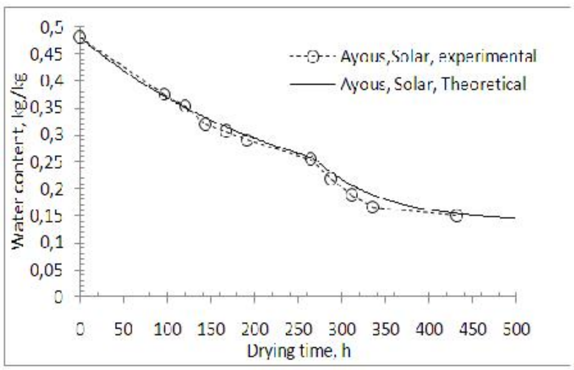


Fig .10. Solar drying kinetic of ayous, from 29th October to 15th November 2004 at Yaoundé-Cameroon

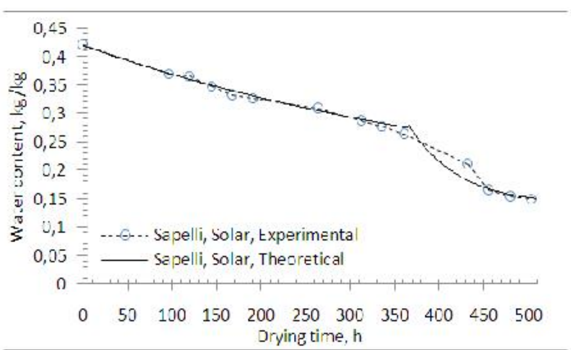


Fig. 11. Solar drying kinetic of sapele, from 29th October to 18th November 2004 at Yaoundé-Cameroon

Table 7 presents the masses (anhydrous and initial) of the samples, the relative differences and the obtained global mass transfer coefficients. We note that the presence of many fragments on the curves are caused by the new stability of the wood temperature each time that the temperature of the air ambient changes. In the case of iroko, global mass transfer coefficient is equal to $1.1033x10^{-5}$ kg/(m^2.s), in the same order than the conventional drying. After 360h, global mass transfer coefficient of sapele is also in the order of 10^{-5} kg/(m^2.s). Before 360h of the drying, this coefficient is in the order of 10^{-6} kg/(m^2.s), such as in the case of ayous during all the drying time. Difference obtained between solar and conventional drying can be caused by the thickness of the board. In effect, according to the literature, global mass transfer coefficient decreases when thickness increases [5,6]. Because the air conditions between solar and conventional drying used are near, it is possible that the global mass transfer coefficient is lower in the case of solar drying caused by the thickness of the board which is almost the double of the thickness of board used in the case of conventional drying.

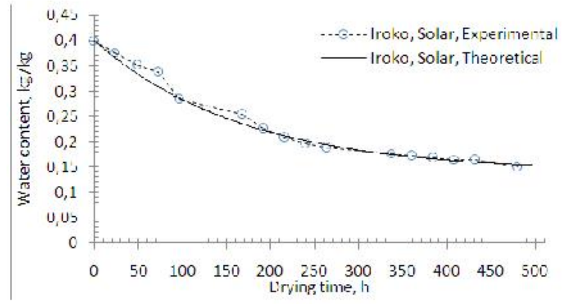


Fig.12. Solar drying kinetic of iroko, from 22th November to 12th December 2004 at Yaoundé-Cameroon

Table 7. Obtained global mass transfers, Solar drying

Parameters	Ayous		Sapele		Iroko
	$t < 264h$	$t \ge 264h$	$t < 360h$	$t \ge 360h$	$\forall t \ge 0$
Temperature	50 ≤ T ≤ 65°C		50 ≤ T ≤ 65°C		50 ≤ T ≤ 65°C
M_i(kg)	5.024		13.83		15.75
M_o(kg)	3.3947		9.7394		11.121
K x10^6 (kg/(m^2.s))	2.4495	7.9609	3.5135	31.622	11.033
E(%)	4.0492		2.2756		2.7548

To correlate the global mass transfer coefficient in function of the parameters of the wood and the drying air, the authors [5,6] have established relation 11 where the parameters a_o, b_o, c_o and p are to determine in function of wood species.

$$\frac{1}{K} = a_o exp\left(\frac{c_o}{T_a}\right) e + b_o exp\left(\frac{c_o}{T_a}\right) V^{-p} exp\left(-\frac{1-\frac{RH}{100}}{X_{fsp}-X_{eq}}\right) \quad (11)$$

K is the global mass transfer coefficient (kg/(m^2.s)), T_a is air temperature in Kelvin, V is air velocity (m/s), RH is air relative humidity in %, X_{fsp} and X_{eq} are the water content respectively in the fiber saturation point and in equilibrium state in decimal, e is the thickness of the board in m.

Applied on temperate woods, the authors [5,6] obtained the parameters a_o, b_o, c_o and p given on the table 8.

Table 8. Parameters of equation 11 given on the literature

Parameters	[5]	[6]
a_o(ms/kg)	0.12	0.2265
[illegible]^2/kg)	23.9	268.9
c_o(K)	2683	2543.6
p(-)	0.8	2.7158

It is very important to determine the same parameters on tropical woods in order to obtain the specificities own of the drying of tropical woods and simulate very well the drying of these woods in the future using relations 5 and 11 which are very simple to use, comparative of the other modeling such as [10].

4. Conclusion

1. Simplified method is appropriated to describe the drying kinetics of Cameroonian tropical woods. But, it is necessary to use the phase where wood temperature becomes constant in the case of conventional drying;
2. Global mass transfer coefficients of tropical woods studied are in the same order than Chilean woods. these are between 2×10^{-5} et 4×10^{-5} kg/(m^2.s) when dryer is conventional with air kinetic is between 0.25 and 1.5m/s, the thickness of board is between 24 and 30 mm, dry temperature equal to 33.5°C and wet temperature is equal to 25°C. For solar drying at Yaoundé from October to December with 50mm of thickness, this coefficient is lower than those obtained on conventional drying with 25mm of thickness;
3. Global mass transfer coefficient decreases when density of wood increases. This coefficient decreases when increases the thickness of board;
4. In general, global mass transfer coefficients obtained are less important than those obtained on temperate woods in the same air and board conditions;
5. A specific study in function of the influence of thermophysical conditions of wood and drying air on the global mass transfer coefficients of African tropical woods is important in order to have the appropriated results in the situation of the variations of air conditions during the drying process such as those used in the industrial reality and in the solar drying process. Thus, determination of the parameters a_o, b_o, c_o and p of equation 11 using tropical wood is necessary.

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References

[1] GTZ. Note technique sur le bois énergie au Cameroun. 2006.

[2] M. Simo-Tagne. Experimental characterization of the influence of water content on the density and shrinkage of tropical woods coming from Cameroon and deduction of their fiber saturation points. IJSR 2014. 3 (6): 510-515.

[3] Alvear M, Broche W, Salinas C, Ananias R.A. Drying kinetic of Chilean coigüe: study of the global drying coefficient. 8th International IUFRO Wood Drying Conference. 383-387, 2003.

[4] Ananias, R.A., Chrusciel, L., Zoulalian, A., Salinas-Lira, C., Mougel, E: Overall Mass Transfer moefficient for wood drying curves predictions, mass transfer in multiphase systems and its applications. Prof. Mohamed El-Amin (Ed.), ISBN: 978-953-307-215-9, InTech, Available from: http://www.intechopen.com/books/mass-transfer-in-multiphase-systems-and-its-applications/overall-masstransfer-coefficient-for-wood-drying-curves-predictions, 2011.

[5] R. A. Ananías, E. Mougel, A. Zoulalian. Introducing an overall mass-transfer coefficient for prediction of drying curves at low temperature drying rates. Wood Science and Technology 2009. 43: (1): 43-56.

[6] L. Chrusciel, E. Mougel, A. Zoulalian, T. Meunier. Characterisation of water transfer in a low temperature convective wood drier: influence of the operating parameters on the mass transfer coefficient. Holz Roh Werkstoff 1999. (57):439-445.

[7] Norme française. Bois- Conditions générales d'essais-Essais Physiques et Mécaniques. 1985.

[8] N. Bekkioui, A. Zoulalian, A. Hakam, F. Bentayeb, A. Sesbou. Modelling of a solar wood dryer with glazed walls. Maderas Ciencia y Tecnologia 2009. (11) 3:191-205.

[9] F. Bentayeb, N. Bekkioui, B. Zeghmati. Modelling and simulation of a wood solar dryer in a Moroccan climate. Renewable Energy 2008. (33):501-506. DOI: 10.1016/j.renene.2007.03.030

[10] M. Simo-Tagne. Laboratory simulation of solar drying for tropical woods: the case of ebony (diospyros crassiflora). International Journal of Thermal and Environment Engineering 2015. 9 (1):1-6. DOI: 10.5383/ijtee.09.01.001.