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Modeling and Simulation of the Drying of Beech Timber (*Fagus sylvatica*) Using Oscillating Regimes

Merlin Simo Tagne[a]*, Yann Rogaume[b], André Zoulalian[b]
[a]*Douala Higher Institute of Technology (DIT), Douala, Cameroon, PO Box 1623*
[b]*University of Lorraine, LERMaB, ENSTIB, Epinal, France, PO Box 1041, 88051 Epinal cedex 9*

Abstract

This paper represents a numerical study of the massive (60mm) and thin (38mm) wood drying using oscillating drying regimes applied on beech timber (*Fagus sylvatica*). All thermo-physical properties relative of studied wood are taken from the literature on appropriate experiments. We showed that Luikov's model can be used to predict temperature and moisture content evolutions using oscillating regimes. First numerically tests on 60mm timber wood consists in increasing and decreasing alternation of the drying parameters (temperature), at the rising 12-15°C and at the descent 10-12°C, every alternation being higher than the precedent with 2-4°C. Second numerical test consists to oscillate the values of equilibrium moisture content with the oscillation amplitudes of ±10% and ±20% at the frequencies of 6hours. These practical experiments are detailed in the literature. Luikov's model gives satisfactory results, according to the experiments obtained in the literature. But, convective transfer coefficients are function of each experiment and we observed a short difference between oscillation amplitudes of ±10% and ±20% on moisture content evolution. Thus, Luikov's model can be a tool to study oscillation drying timber in order to reduce consumption of energy during the drying process.

Keywords: *Drying, Heat and Mass Transfer, Luikov's Model, Simulation, Oscillating Regimes, Beech Wood.*

1. Introduction

In the context of increasing energy demand, it is important to optimize utilization of energy and theirs resources in industry. In the forest industries, conventional drying is used in great majority. Nowadays, it is know that conventional drying consumes much energy. Some experiments on the oscillation drying of wood showed that this process permits to dry the wood with a short drying time and taken into consideration drying quality. For example, Alexandru says that Oscillating regimes reduced the duration of the drying in the conventional table with 50% [1]. Rémond *et al.* assume that oscillating conditions reduced drying stresses [2]. In the literature, studies on the oscillating drying are experimental [1,2,3]. Numerical studies are recommended to selected amplitudes and frequencies of oscillations because these are quick, economic and non-destructive. Rémond *et al.* were used computational model *TransPore* to study the drying of temperate wood during the flying wood test [2]. This study gives the good results according to the experiment results. But, what we obtained such as results when a classical model is used? The answer of this question is much important in order to see what modification to bring on the old program which uses classical model developed after the years 1940 as Luikov's model.
In this study, we used the model of Luikov (1946) to simulate numerically the drying of beech wood (Fagus sylvatica) in the same conditions than the experimental oscillating regimes obtained by Alexandru and Milic and Kolin [1,3].

2. Materials and Methods

2.1. Materials

We have used experiments on beech wood (Fagus sylvatica) present in the literature to validate numerical measures given by Luikov's model. It is a timber very difficult to dry and less stable during his utilization. Benoît gives more indications relative on physical and mechanical properties of beech [4].

* Corresponding author. Tel.: 00237694852402
E-mail: simotagne2002@yahoo.fr

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2.2. Methods

2.2.1. Experiments

Alexandru tests (first test) experimentally the drying on 60mm timber wood and consists in alternative increasing and decreasing of the drying parameters (temperature), at the rising 12-15°C and at the descent 10-12°C, every alternation being higher than the precedent with 2-4°C [1].
Milic and Kolin test (second test) experimentally the drying on 38mm timber wood and consists to oscillate the values of equilibrium moisture content with the oscillation amplitudes of ±10% and ±20% at the frequencies of 6hours. The drying table used is given in table 1 [3].

Table 1. Conventional drying schedule of Beech on 38mm [3]

MC (%)	temp. (°C)	EMC (%)
60	37	15
55	38	15
50	38	14.6
45	38	14
40	38	13.6
35	40	13.1
30	43	12.1
25	47	9.2
20	52	6.8
15	58	5.4
10	62	4.4
5	62	4.4

2.2.2. Modeling

2.2.2.1 Luikov's model and hypothesis

It is very difficult to use all drying models without simplification because drying process has the multidimensional characteristics and the wood samples present many thermo-physical parameters which are unknown [5]. Therefore, in this work we assume the following hypothesis:
*A size of sample to be dried remains constant, homogeneous and chemically inert;
*As soon as the drying begins, water that comes out from wood drying is in vapor and/or free water form, bound water is extracted when the fiber saturation point is obtained;
*Symmetric drying, that is the median of the wood plank has maximal temperature and water content;
*Heat transfer by convection takes place only at the level of thermal layers limit which borders the samples;
*Neglect transfer on the lateral faces. Heat transfer is controlled by the thickness of the planks, which is smaller than width and length;
*Gravity effect and hydraulic conductivity of wood are neglected;
*The losses inherent in the dryer are ignored;
*Air and water are assumed incompressible.
Figure 1 shows the geometry of the sample and the directions of gas flow and mass and heat transfers.

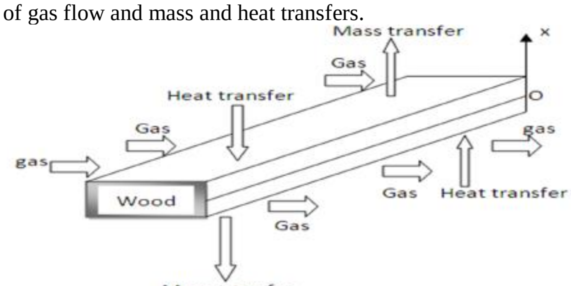


Fig.1: Schematic representation of the geometry

Luikov's model gives similar equations with others parameters. Hypothesis and equations of this model are given by [6]. In one dimension we have the following equations (1):

Heat transfer:

$$\rho_s c_p \frac{\partial T}{\partial t} = \left(\lambda + \frac{\varepsilon L k_m \delta}{c_n}\right)\frac{\partial^2 T}{\partial x^2} + \varepsilon L k_m \frac{\partial^2 U}{\partial x^2} \quad (1a)$$

Boundary condition on the heat transfer (at the surfaces):

$$-\lambda \frac{\partial T}{\partial x} = h_c (T - T_{air}) + (1-\varepsilon) L \alpha_m (U - U_{air}) \quad (1b)$$

Mass transfer:

$$\rho_s c_m \frac{\partial U}{\partial t} = \left(\frac{k_m \delta}{c_m}\right)\frac{\partial^2 T}{\partial x^2} + k_m \frac{\partial^2 U}{\partial x^2} \quad (1c)$$

Boundary condition on the mass transfer (at the surfaces):

$$-k_m \frac{\partial U}{\partial x} = \left(\frac{k_m \delta}{c_m}\right)\frac{\partial T}{\partial n} + \alpha_m (U - U_{air}) \quad (1d)$$

We note that Messaoud Nabhani and Yves Fortin recommend adapting this parameter in function of drying process with a corrective coefficient [7]. For this reason we have changed α_m by $\alpha_m^{'} = \beta \alpha_m$.

ε : ratio of vapor diffusion coefficient to coefficient of total moisture diffusion (-);

δ :thermal gradient coefficient (K^{-1});

k_m :moisture conductivity($kg.m^{-1}.s^{-1}.°M^{-1}$);

c_m:moisture capacity($kg.kg^{-1}.°M^{-1}$);

α_m , $\alpha_m^{'}$:convective mass transfer coefficient in Luikov model($kg.m^{-2}.s^{-1}.°M^{-1}$);

β :corrective factor varied between 0 and 1 [7] (-);

U:moisture potential of wood (°M) defined by Luikov and given by $H = U c_m$;

n: normal. The others parameters are same previously (-).

It is clear those new parameters like ε and β which change during the drying and which cannot give physical explanation complicate a utilization of this model.

2.2.2.2 Parameters used in the simulations

*Thermal conductivity of wood (W/(mK)) taken from [8]:

$$a = \frac{\circ}{\circ_l}(0.2003 + 0.00548 H) + 0.02378 \quad (2)$$

H in %

*Specific heat capacity of wood (kJ/(kg.K)) taken from [8] :

$$C_p = \frac{C_{po} + 0.01 H C_{pw}}{1 + 0.01H} + H(-0.06191 + 2.36 * 10^{-4} T - 1.33 * 10^{-4} H) \quad (3.a)$$

H in %

$C_{po} = 0.1031 + 0.003867T$ and $C_{pw} = 4.19 kJ/(kg.K)$ (3.b)

T in Kelvin. Second term of second member of (3a) is equal to zero in a non hygroscopic domain, domain that is limited by the water content at the fibers saturation point given by the equation [9]:

$$H_s=0.3161-1.327\times10^{-3}(T-273.15) \quad (4)$$

*Latent heat of vaporization (J/kg) taken from [10]:

$$L=(3335-2.91T)*10^3 \quad (5)$$

L in J/kg, H in % and T in K

*Desorption heat of the water adsorbed (J/kg) taken from [11]:

$$E=1170.4\times10^3\exp(-0.14H) \quad (6)$$

E in J/kg and H in %.

*Mass diffusion coefficient of the wood(m^2/s) taken from [12]:

$$D_H=1.95\times10^{-10}m^2/s \quad (7)$$

*Density of the water (kg/m^3) taken from [13]:

$$\rho_l = -0.0038\,T^2 - 0.0505\,T + 1002.6 \quad (8)$$

*Activation energy of the wood (J/mol) taken from [14]:

$$E_b = 4.18(9200 - 7000X_{eq}) \quad (9)$$

*Equilibrium water content (kg/kg) taken from [8]:

$$X_{eq} = \frac{18}{W}\left[\frac{K.HR}{1-K.HR} + \frac{K.HR.K_1 + 2.K_1.K_2.K^2.HR^2}{1+K_1.K.HR+K_1.K_2.K^2.HR^2}\right] \quad (10.a)$$

with :

$$W=349+1.29T_{air}+0.0135{T_{air}}^2 \quad (10.b)$$

$$K=0.805+0.000736T_{air}-0.00000273{T_{air}}^2 \quad (10.c)$$

$$K_1=6.27-0.00938T_{air}-0.000303{T_{air}}^2 \quad (10.d)$$

$$K_2=1.91+0.0407T_{air}-0.000293{T_{air}}^2 \quad (10.e)$$

T_{air} is the air temperature in °C and HR is the air humidity in decimal.

We have used this relationship only during numerical simulation relative of first test. The others simulations used equilibrium water content given in the drying tables.

*Density of wet wood (kg/m^3) taken from [8]:

$$\rho(H) = 1000.\,G_m\left(\frac{H(\%)}{100}+1\right) \quad (11)$$

Where G_m is the specific gravity equal to 0.68 for beech wood [8].

2.2.2.3 Parameters of Luikov's model

They are taken in the literature. We have:

*Ratio of vapor diffusion coefficient to coefficient of total moisture diffusion:

Messaoud Nabhani and Tremblay show that this parameter varied between 0 (in the start of drying) and 1 (in the end of drying) also, this ratio is equal to 0.33 when water content varied between 220 and 20% [15]. According to Kulasiri and Woodhead (2004), the value of ε depends on the nature of the material [16]. In this study, we have taken ε=0.3 [6,7].

*Thermal gradient coefficient (K^{-1}):

When water content of porous media changes from 60 to 0%, Kulasiri and Woodhead (2004) show that thermal gradient coefficient vary from 0.1 to $0K^{-1}$ respectively [16]. We have taken $\delta=0.025K^{-1}$ [6].

* Moisture conductivity:

$k_m=1.8\times10^{-8}kg.m^{-1}.s^{-1}.°M^{-1}$ taken from [6].

* Moisture capacity:

$c_m=0.01kg.kg^{-1}.°M^{-1}$ taken from [6].

*Convective mass transfer coefficient in Luikov's model:

Convective heat (h_c) and mass transfer (h_m) coefficient are function of gas velocity V_a and variations of temperature during experiment. We have a laminar flow if Reynold's number Re is inferior to 2300 and we have turbulent flow when Re is superior or equal to 2300. Hydraulic diameter is given by D_h=2e' where e' is the distance between two consecutive rows of the samples. If study is based on one piece only, hydraulic diameter is the length of the sample. Thus:

$$h_c = \frac{\lambda_a Nu}{D_h} \quad (12)$$

We used $h_c = 11.2W/(m^2.K)$ taken from [17].

Where λ_a is the thermal conductivity of air and Nu is the Nusselt's number.

Also,

$$h_m = \frac{D_H Sh}{D_h} \quad (13)$$

$\alpha_m = c_m.\rho_s.h_m$ and $\alpha'_m = \beta\alpha_m$ with $0 < \beta < 1$. The values of α'_m were obtained by an inverse method.

For numerically simulate drying with a thickness other than 38mm, we have used table 2 given by [18].

Table 2. Drying table of beech wood [18]

H(%)	Temperatures		HR (%)	X_{eq} (%)	G,gradient of drying
	Dry(°C)	Humid(°C)			
green	50	47	85	17	-
35	50	46	80	15	-
32	55	50	75	13	-
30	60	53	70	11	2.7
25	65	55.5	62	9	2.8
20	70	57	52	7	2.9
15	70	50	35	5	3

2.2.3. Numerical method of the resolution

For find solution of equations, we have utilized the finite difference method. This method permits to approximate solution by the use of Taylor's series. Implicit form is adopted at the resolution of differential equations that is less strongly coupled and to have the coefficients that change less. Coupling of these differential equations cannot envisage an analytical resolution. The wood plank layer is divided into 2N+2 series of thin layers, with in a half thickness, the spaces orders for j in advanced from 1 at N+1. Similarly, the equations of mass and heat are written in discrete form as:

$$\begin{cases} -AH_{j+1}^{i+1}+(1+2A)H_j^{i+1}-AH_{j-1}^{i+1}=H_j^i-2DT_j^i+DT_{j-1}^i+DT_{j+1}^i \\ -BT_{j-1}^{i+1}+(2B+1)T_j^{i+1}-BT_{j+1}^{i+1}=T_j^i-2CH_j^i+CH_{j+1}^i+CH_{j-1}^i \end{cases} \quad (14.a)$$

with :

$$A=\frac{D_{HH}\,\Delta t}{(\Delta x)^2};\ B=\frac{a+D_{TT}}{{}^{\circ}{}_{s}C_p(\Delta x)^2}\Delta t;\ C=\frac{D_{TH}\Delta t}{{}^{\circ}{}_{S}C_P(\Delta x)^2};\ D=\frac{D_{HT}\,\Delta t}{(\Delta x)^2} \quad (14.b)$$

A, B, C and D are given at the knots (i,j) with :

$$x_j = x_0 + jh,\ t_i = t_0 + il \quad (15)$$

We have put the system (14.a) in the following matrix form:

$$[E_j][G_j^{i+1}]+[F_j][G_{j-1}^{i+1}+G_{j+1}^{i+1}]=[H_j] \quad (16.a)$$

With:

$$[E_j]=\begin{bmatrix}2A+1 & 0\\ 0 & 2B+1\end{bmatrix},[F_j]=\begin{bmatrix}-A & 0\\ 0 & -B\end{bmatrix}[H_j]=\begin{bmatrix}H_j^i+DT_{j-1}^i-2DT_j^i+DT_{j+1}^i\\ T_j^i+CH_{j-1}^i-2CH_j^i+CH_{j+1}^i\end{bmatrix},[G_j^i]=\begin{bmatrix}H_j^i\\ T_j^i\end{bmatrix} \quad (16.b)$$

In order to have a recursive solution, we have considered that:

$$[G_j^{i+1}]=[¥_j]-[\quad_j]^{-1}[F_j][G_{j+1}^{i+1}] \quad (17.a)$$

With

$$[¥_j]=\frac{[H_j]-[F_j][¥_{j-1}]}{[\quad_j]};\ [\quad_j]=[E_j]-\frac{[F_j][F_{j-1}]}{[\quad_{j-1}]} \quad (17.b)$$

Results can be progressively obtained. We have translated our program in the class 77 of Fortran to generate all numerical results. Microsoft Excel is used to process and display the results. The time step and space step are respectively 1700s and $6.25\text{x}10^{-4}$m [19]. Initial temperature of samples is 30°C. In each drying time t_i, from local values of humidity and the temperature of wood, average values are evaluated through relations 18.a and 18.b.

$$T^i = \frac{\sum_{J=1}^{N+1} T_J^i}{N+1} \quad (18.a)$$

$$H^i = \frac{\sum_{J=1}^{N+1} H_J^i}{N+1} \quad (18.b)$$

These are the values that will be represented on the following figures.

3. Results and discussions

Figure 2 below presents evolution of theoretical and experimental water content using oscillating drying (test 1) on 60mm of beech timber. We saw that Luikov's model gives good results when water content is above the fiber saturation point. Below this point, numerical values are superior to experiment values. It is possible that equilibrium moisture content presented in relation (10a) is not appropriated to describe equilibrium points.

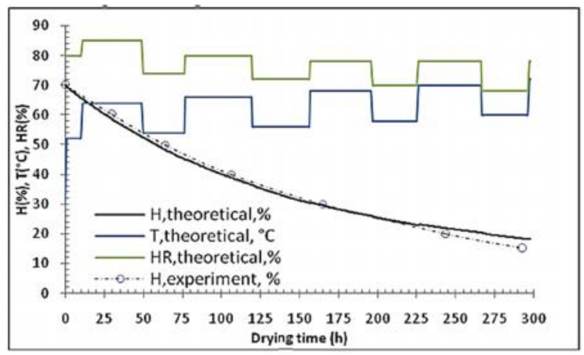


Fig. 2. Experimental and theoretical values of Water content of 60mm Beech wood using test 1 (α'_n =5.5x10^{-7} kg.m^{-2}.s^{-1}.°M^{-1})

Using only numerically results through Luikov's model, figure 3 shows that table 2 and test 1 conditions give a same result when water content is above 45%, oscillation conditions presents a low results when water content is inferior than 40% and and superior than 20%, and drying table 2 conditions present a low results when water content is below 20%. But, it is important to notice that conditions of table 2 are hard than oscillation drying (test 1), seen evolutions of relative humidity of each drying condition. It is clean to prefer oscillating drying condition to drying table 2 because, drying table 2 gives more stresses in the beech timber and gives nearly the same results than oscillating conditions given by test 1.

In figure 4, we seen that if in hygroscopic domain we taken conditions of the drying table 2 and in the non hygroscopic domain we taken the conditions of oscillating domain, we have nearly the same evolution of water content experimentally obtained during test 1 by Alexandru [1]. In this condition, if final water content is below 20%, then oscillating condition reduced the drying time obtained with drying table 2 by 12 hours.

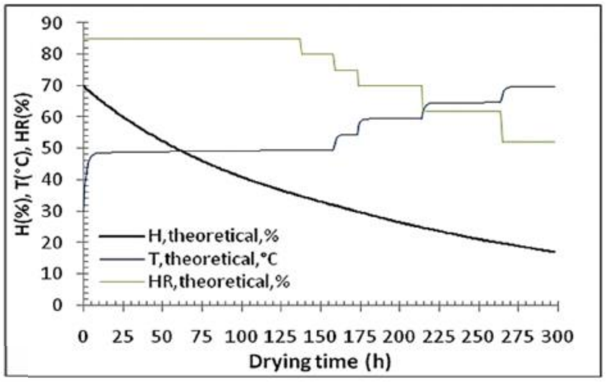


Fig.3a. Water content evolution using table 2 (e=60mm, α'_m =5.5x10^{-7} kg.m^{-2}.s^{-1}.°M^{-1})

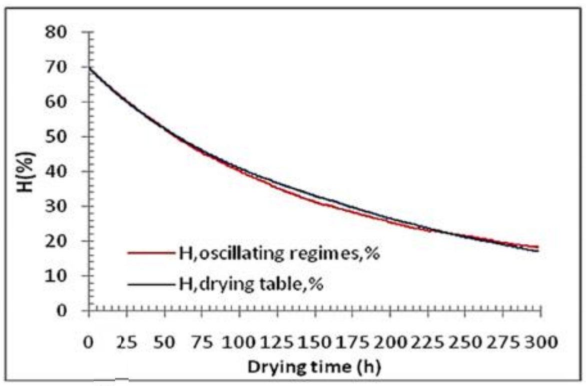


Fig. 3b. Comparison between results using test 1 and drying table 2 (e=60mm, α'_m =5.5x10^{-7} kg.m^{-2}.s^{-1}.°M^{-1})

Figures 5 and 6 show results obtained after using test 2 conditions applied on 38mm beech timber. In each figure, part a is our numerical result and part b is experimental result taken from [3]. We saw that evolution of dry temperature given by ours results respect conditions of table 1. This evolution is not respected during experiment. According to program of table 1, dry temperature is fixed in function the values of moisture content and oscillation of equilibrium water content is obtained after modification of the value of relative humidity (or humid temperature with adding or reducing the vapor of water). For this reason, non-regularity evolution of experimental dry temperature can be the difficulty to modify the value of equilibrium water content without to modify dry temperature. Thus, it is clear to see the modification of water content such as experimental results because dry temperature more influences directly the thermo-physical parameters of wood.

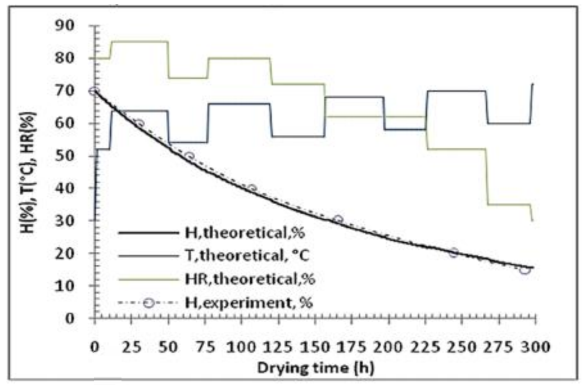


Fig. 4a. Water content evolution using modified test 1 conditions (e=60mm, α'_m =5.5x10^{-7} kg.m^{-2}.s^{-1}.°M^{-1})

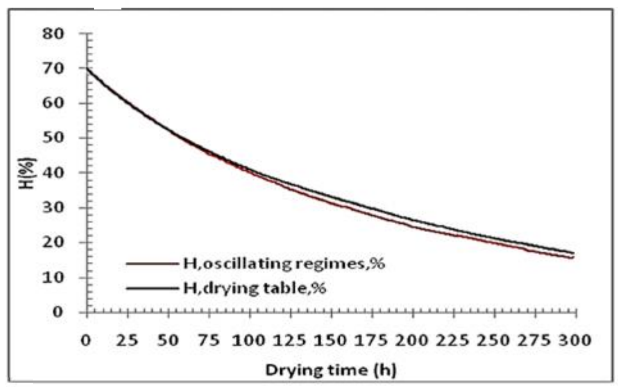
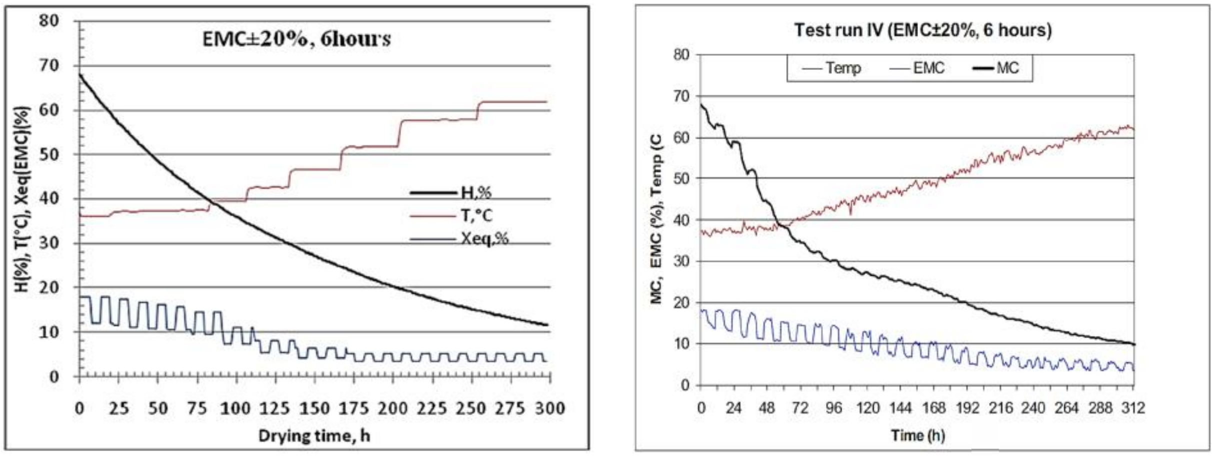


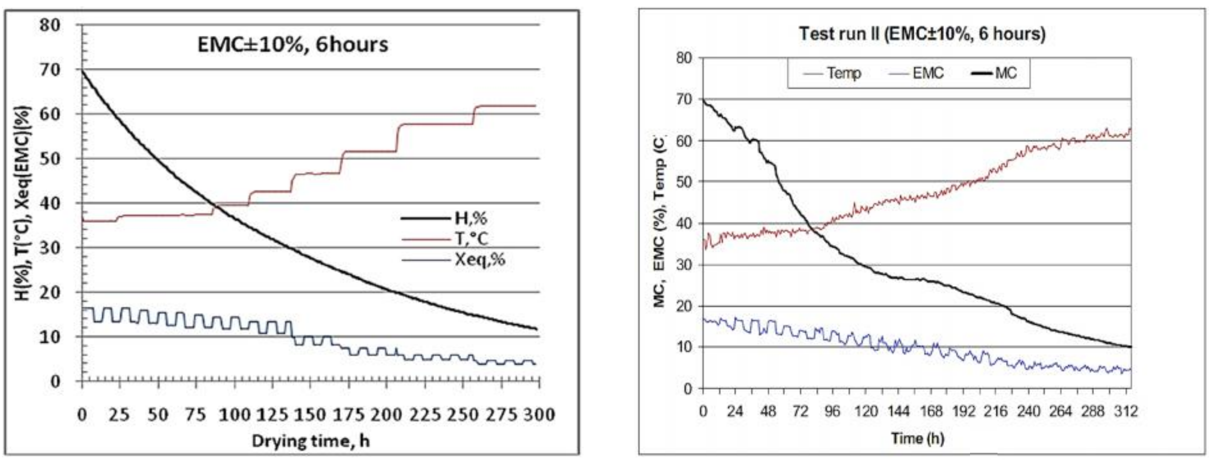
Fig. 4b. Comparison between Water content evolution using modified test 1 with result using table 2 conditions (e=60mm, α'_m =5.5x10^{-7} kg.m^{-2}.s^{-1}.°M^{-1})

Figures 5 and 6 also show that, with the same frequency of equilibrium water content oscillation, numerical results of water content evolutions present less difference between EMC±10% and EMC±20% oscillations.



a) Ours results **b) Experimental results [3]**

Fig. 5. Numerical(a) and experimental (b) evolutions of water content using test 2 and table 1 conditions.e=38mm,α'_m=3.5x10^{-7} kg.m^{-2}.s^{-1}.°M^{-1}, EMC±20%, 6hours.



a) Ours results **b) Experimental results [3]**

Fig. 6. Numerical(a) and experimental(b) evolutions of water content using test 2 and table 1 conditions.e=38mm, α'_m=3.5x10^{-7} kg.m^{-2}.s^{-1}.°M^{-1}, EMC±10%, 6hours.

Convective mass transfer coefficient α'_m varied with experiment. In the first test, we have α'_m=5.5x10^{-7} kg.m^{-2}.s^{-1}.°M^{-1} and α'_m =3.5x10^{-7} kg.m^{-2}.s^{-1}.°M^{-1} in the second. We know that this coefficient depends to temperature, air velocity and hydraulic diameter. Experiments 1 and 2 obtained by Alexandru [1]and Milic and Kolin [3] respectively not give characteristics of wood stack. They give only the thickness of the plank. For this reason, we have given the values of α'_m by an inverse method. At the high temperature (T=200°C), [6] obtained the value 1.6x10^{-5} kg.m^{-2}.s^{-1}.°M^{-1}. In the low temperature, this parameter is low if the same others parameters are used. In the first test, maximum temperature is 75°C and it is 62°C in the second. Thus, it is possible that the great value of α_m obtained in the first test (α'_m =5.5x10^{-7} kg.m^{-2}.s^{-1}.°M^{-1}) by comparison to the value obtained in the second test (α'_m =3.5x10^{-7} kg.m^{-2}.s^{-1}.°M^{-1}) is explained by these different maximum values of temperature.

4. Conclusion

Drying kinetics of 60mm and 38mm beech timber was simulated using oscillating regimes. A better fit was obtained using Luikov's model (1946) and the thermo-physical parameters on wood are previously published in the literature. Experimental drying kinetic used for validate numerical results were published by Alexandru [1] and Milic and Kolin [3]. This work confirms the possibility to reduce drying time and the prize of the wood drying process when oscillating regimes is used. Some differences between experimental and numerical results are probability caused by the relationship used to give equilibrium water content. Also, it is important to calculate experimentally all thermo-physical parameters of transport for this wood specie. Nevertheless, the numerical results describe correctly the water content variation of beech timber under oscillating regimes. But, it is difficult to estimate the convective mass transfer coefficient of Luikov's model. In order to easily use Luikov's model in oscillating regimes, studies on the estimation of convective mass transfer coefficient are necessary.

Nomenclature

A,B,C,D	Elements of the matrix of transfers
C_p	Specific heat capacity of wet wood, J/(kg.K)
c_m	Moisture capacity, kg.kg^{-1}.°M^{-1}
D_H	Diffusion coefficients of bound water at a gradient humidity, m^2/s
D_h	Hydraulic diameter, m
E	Heat desorption of the water absorbed, J/kg
e	Thickness, mm
E_b	Activation energy of the wood, J/mol
E_i,F_i,G_i	Coefficients of the matrix of transfers
H	Water content of wood, kg/kg
H_o	Initial water content of wood, kg/kg
H_s	Humidity at the fiber saturation point, kg/kg
HR	Air relative humidity
h_c	Heat transfer coefficient, W/(m^2.K)
h_m	Global mass transfer coefficient, m/s
k_m	Moisture conductivity, kg.m^{-1}.s^{-1}.°M^{-1}
L	Latent heat of the vaporization of liquid water, J/kg
R	Universal gases constante, 8.314J/(mol.K)
T	Temperature of wood, K
t	Drying time, s
T_{air}	Temperature of air, K
T_o	Initial temperature of wood, K
T_s	Air dry temperature, K
U	Moisture potential of wood, °M
U_{air}	Moisture potential of air, °M
V_a	Air velocity, m/s
x	X-axis according to the thickness, m
X_{eq}	Equilibrium water content, kg/kg

Greek Symbols

~	Thermomigration coefficient also calling soret effect coefficient, K^{-1}
α_m	Convective mass transfer coefficient in Luikov model, kg.m^{-2}.s^{-1}.°M^{-1}
β	Corrective factor
δ	Thermal gradient coefficient, K^{-1}
a	Thermal conductivity of wet wood, W/(m.K)
λ_a	Thermal conductivity of air, W/(m.K)
ε	Ratio of vapor diffusion coefficient to coefficient of total moisture diffusion
ρ	Wood mass density at the humidity H, kg/m^3
ρ^l	Density of water, kg/m^3
ρ_s	Density of anhydrous wood, kg/m^3

Non-dimensional Numbers

i,j	Order of the iteration
n	Normal
Nu	Nusselt number
Re	Reynolds number
Sh	Sherwood number

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