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Overall Mass-Transfer Coefficient for Wood Drying Curves Predictions

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1. Introduction

Wood is a biological material, hygroscopic, anisotropic and highly heterogeneous. To predict the wood drying rate, the drying kinetics need to be described. The wood drying kinetics can be described by three periods. Except in the first drying period, where the internal resistance of the water transfer can be neglected, it is necessary to take into account the internal transfer resistance during the second and third drying periods. It is sufficient to combine both the internal and external resistances, expressing the drying rate according to an overall mass transfer coefficient K. The driving force can be a physical characteristic of water in either the gas or solid phase. Karabagli et al. (1997) and Chrusciel et al. (1999), then Ananías et al. (2009a, 2009b) opted for an absolute average wood moisture content difference. The overall mass transfer coefficient is characterized by four operating parameters: wood thickness, air velocity, air temperature and air relative humidity. In general, K includes the internal resistance of the moisture movement through wood and the external resistance of the transfer of moisture from wood surface to the air. This chapter is a review of model permitting the determination of wood drying rate represented by an overall mass transfer coefficient, noted K, and a driving force expressed as the difference between the average wood moisture content and the equilibrium wood moisture content.

2. Wood drying kinetics

The drying rate Φ of wood can be represented by the derivative of the absolute wood moisture content ($-d\bar{x}/dt$), then

$$\Phi = \frac{-M_0}{A}\left(\frac{d\bar{x}}{dt}\right) \tag{1}$$

Also, the drying rate can be characterized by the transfer resistance of the gas phase (Bramhall 1979a, 1979b). It is:

$$\Phi = k_G \cdot (P_i - P_v) \tag{2}$$

The transfer coefficient k_G can be estimated by correlating with values reported in the literature, but the evaluation of Φ requires the knowledge of the partial pressure P_i. The relationship between this pressure and the average wood moisture content is not evident, and this relationship is applicable only during the first drying period, because P_i, the vapor pressure, is only equal to the saturated vapor pressure of the liquid water at the interface temperature.

Van Meel (1958) proposed a characteristic drying curve to represent the three drying phases with a relationship between the reduced drying rate Φ^+ and the non-dimensional parameter φ

$$\varphi = \frac{\bar{x} - x^*}{\bar{x}_C - x^*} \tag{3}$$

Where $\bar{x}$, $\bar{x}_C$, x* indicate the average wood moisture content, the wood moisture content at the end of the first drying period, and the wood moisture content at the end of drying (equilibrium moisture content), respectively.

The equilibrium moisture content x* can be determined by Simpson correlations (Siau 1984):

$$x^* = \left[\frac{w_1 \cdot w_2 \cdot RH}{1 + w_1 \cdot w_2 \cdot RH} + \frac{w_2 \cdot RH}{1 - w_2 \cdot RH}\right] \cdot \frac{18}{w_3} \tag{4}$$

Where RH is the relative humidity

$$RH = \frac{P_v}{P_s} \tag{5}$$

In wich Pv and Ps are defined as:

$$P_v = \left\{P_{sw} - \frac{\left(1.3332 \cdot 10^5 - P_{sw}\right) \cdot \left(T - T_w\right)}{1546 - 1.44 \cdot T_w}\right\} \tag{6}$$

$$P_s = 133.32 \cdot e^{\left(51.29 - \frac{6651}{T_K} - 4.53 \cdot \ln(T_K)\right)} \tag{7}$$

$$P_{Sw} = 133.32 \cdot e^{\left(51.29 - \frac{6651}{T_{Kw}} - 4.53 \cdot \ln(T_{Kw})\right)} \tag{8}$$

And w_1, w_2 and w_3 are coefficients as a function of temperatures T (°C)

$$w_1 = 4.737 + 0.0477 \cdot T - 0.0005 \cdot T^2 \tag{9}$$

$$w_2 = 0.7095 + 0.0017 \cdot T - 5.5534 \cdot 10^{-6} \cdot T^2 \tag{10}$$

$$w_3 = 223.385 + 0.6942 \cdot T + 0.0185 \cdot T^2 \tag{11}$$

Φ^+ represents the relation between the drying rate and the maximum drying rate obtained during the first drying period. The maximum drying rate can be estimated by equation 2, where the partial vapor pressure Pi is replaced by the saturated pressure of the liquid water at the interface temperature. However, Ananias et al. (2009a) used the heat and mass transfer analogy to estimate the maximal drying rate using the equation:

$$\Phi_{MAX} = \frac{h \cdot (T - T_W)}{\Delta h_v} \tag{12}$$

Where h is the external heat transfer coefficient, which can be estimated by various correlations according to the wood drier geometry:

$$h = 0.023 \cdot \left(\frac{v \cdot d_H}{\upsilon} \right)^{\frac{4}{5}} \cdot \left(\frac{v \cdot \rho \cdot C_{Pa}}{\lambda} \right)^{\frac{1}{3}} \cdot \frac{\lambda}{d_H} \tag{13}$$

In wich υ, ρ, λ and C_{Pa} are the air properties defined as following (Jumah et al. 1997):

$$\upsilon = \frac{\mu}{\rho} \tag{14}$$

$$\mu = 1.691 \cdot 10^{-5} + 4.984 \cdot 10^{-8} \cdot T_K - 3.187 \cdot 10^{-11} \cdot T_K^2 + 1.319 \cdot 10^{-14} \cdot T_K^3 \tag{15}$$

$$\rho = \frac{353}{T_K} \tag{16}$$

$$\lambda = 0.02425 + 7.889 \cdot 10^{-5} \cdot T_K - 1.79 \cdot 10^{-8} \cdot T_K^2 - 8.57 \cdot 10^{-12} \cdot T_K^3 \tag{17}$$

$$C_{Pa} = 1.0092 - 4.0403 \cdot 10^{-2} \cdot T_K + 6.1759 \cdot 10^{-4} \cdot T_K^2 - 4.097 \cdot 10^{-17} \cdot T_K^3 \tag{18}$$

With d_H and Δh_v calculated as:

$$d_H = \frac{4 \cdot S}{W_P} \tag{19}$$

$$\Delta h_V = 2503 - 2.43 \cdot T_K \tag{20}$$

Van Meel's characteristic drying curve requires the knowledge of the maximum drying rate and the average wood moisture content $\bar{x}_C$, corresponding to the transition between the first and second drying periods.

The concept of a characteristic drying curve is variously validated by the works of Moyne (1984), Basilico (1985), Moser (1992), Keey (1994), Martin et al. (1995), Pang (1996a) in convective wood drying at both high and very high temperatures, but the first drying period is rarely observed. For parameter φ values below 1, these authors have demonstrated that a functional relationship for Φ might be developed in terms of φ.

Except during the first drying period, where the internal resistance of the water transfer can be neglected, it is necessary to take into account the internal transfer resistance during the second and third drying periods. It is sufficient to combine both the internal and external

resistances, expressing the drying rate according to an overall mass transfer coefficient K. In this stage, the driving force can be a physical characteristic of water in either the gas or solid phase. Karabagli et al. (1997) and then Chrusciel et al. (1999) opted for an absolute average wood moisture content difference. Consequently, the drying rate is expressed as:

$$\Phi = K \cdot (\overline{x} - x^*) \tag{21}$$

In general, K includes the internal resistance of the moisture movement through the wood and the external resistance of the transfer of moisture from the wood surface to the air.

Ananias et al. (2009a) applied the drying model proposed by Van Meel and justified the phenomenological drying model recommended by Karabagli et al. (1997) and Chrusciel et al. (1998). According to Ananias et al. (2009a), these curves do not show the period where the drying rate is constant nor the case when the initial wood moisture content is of the order of 100 %. The first drying period is not observed. This observation is also reported by other authors (Basilico 1985, Moser 1992), who suggest that the absence of the first drying period is due to the low initial wood moisture content values. However Keey et al. (2000) propose that with hardwoods and the heartwood of sapwoods, the critical moisture content is probably the initial value.

Ananias et al (2009a) affirm that the drying rate decreases during the second and third drying period, and estimate that the relationship between the drying rate and the driving force ($\overline{x}$ -x*) is substantially linear. They believe that under constant operating conditions (temperature, humidity and air velocity), the overall mass- transfer coefficient K (equation 21) is substantially constant, justifying the phenomenological law proposed by Karabagli et al. (1997) to express the drying rate. They have not observed a period of constant drying rate even when the initial wood moisture constant was high. Ananias et al (2009a) show that the highest point of the drying curves depends remarkably on the wood thickness, air velocity and air temperature (Fig. 1)

By extrapolation of these linear relationships in the limit value of Φ^+ equal to 1, Ananias et al. (2009a) obtain the critical value of the average wood moisture content, $\overline{x}_C$. They show that the critical wood moisture content depends on all of the studied operating parameters and that they are in a range of absolute wood moisture content between 56.3 and 138.3 %.

According to Ananias et al. (2009a), the $\overline{x}_C$ values cannot be known a priori. Van Meel's representation does not lead to a unique characteristic drying curve. From these representations, they only obtained the existence of a considerably linear relationship between the drying rate and the driving force ($\overline{x}$ -x*), which confirms the hypothesis of Karabagli et al. (1997) for the overall transfer coefficient K: that an overall mass transfer coefficient remains constant during the kiln drying cycle when the operating conditions temperature, humidity relative and air velocity are also maintained constant.

Ananias et al (2009a) show that for all the kiln-drying runs and for the analyzed operating conditions, the average relative error is below 7 %, justifying the selection of the phenomenological drying rate modeling and the hypothesis of a constant overall mass-transfer coefficient. However, since the critical moisture content of the Van Meel's characteristic drying curve and the overall mass-transfer coefficient K depend on the operating conditions, the operating conditions will have a varying influence on the internal and external resistance.

The influence of the operating parameters is demonstrated by Chrusciel et al. (1999). They show that the global mass transfer coefficient K could be represented by two partial mass transfer coefficients, it is, K_g in the gas phase (air) and K_s in the solid phase (wood). Then the water vapor flow rate exchanged between wood and the drying air is estimated by:

$$\phi = K_g \cdot A \cdot (H_S - H) = K_S \cdot A \cdot (x_C - x_S) \tag{22}$$

Where (H_S-H) is the specific humidity slope between the air interface that is in equilibrium with the wood surface and the drying air flow. And (x_C-x_S) is the wood moisture content slope between the wood-core and the wood-surface.

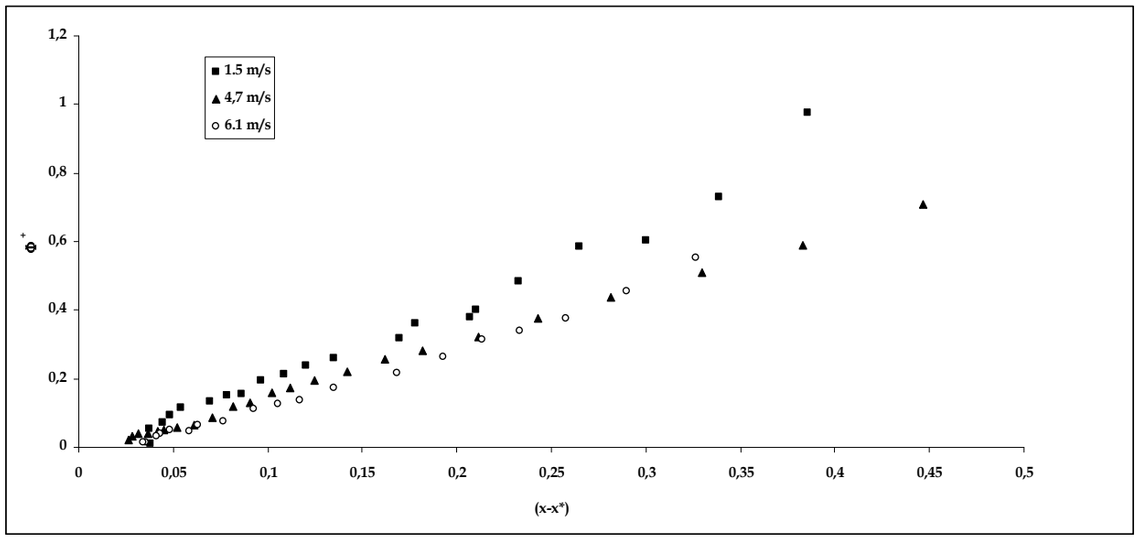


Fig. 1. Effect of air velocity on wood drying rate (After Ananias et al. 2009a)

Suppossing that x_C is not too different from the average x-value and linking the specific humidity (H_S) to the wood moisture content at the interface (x_S) by a proportional coefficient (m), the following equation is obtained

$$H_S = m \cdot x_S \tag{23}$$

Assuming that at the end of the drying cycle, H_S=H and x_S=x*, then the relation between air humidity and wood moisture content is

$$H = m \cdot x^* \tag{24}$$

The above equations (22)-(24) then becomes

$$\frac{1}{K} = \frac{1}{K_S} + \frac{1}{m \cdot K_G} \tag{25}$$

Or

$$\frac{1}{K} = R_I + R_E \tag{26}$$

According to Ananias et al (2009a), the internal resistance R_I is proportional to wood thickness and the external resistance R_E depends on air velocity according to the law of type v^{-n} , where the exponent n varies between 0.5 and 1.

Chrusciel et al. (1999) have shown that the inverse of K, which can be assimilated to a global mass transfer resistance, is a decreasing exponential function of the residual air desiccation ratio z (z = 1 – RH/100).

It is assumed that the global mass transfer resistance 1/K is the sum of two mass transfer resistances: one characterizing the solid phase (wood) and the second one the gas phase (wet air). It is supposed that only the resistance in the gas phase depends on the relative humidity RH and the air velocity v of the air while only the resistance in the solid phase depends on the wood thickness.
It is hard to determine separately the influence of the air temperature on the gas resistance from the one on the solid phase. It is also difficult to distinguish the influence of the air relative humidity from the one of the air temperature on the global mass transfer coefficient. However, it has been demonstrated that the variations of K as a function of the air temperature can be represented by an Arrhenius law. It is then supposed that the influence of T on the two local mass transfer resistances is quite similar. All these considerations permit to propose a general correlation for the global mass transfer resistance:

$$\frac{1}{K} = \alpha + \beta \cdot \exp\left(\frac{-z}{x_{PSF} - x^*}\right) \tag{27}$$

and

$$\alpha = a_0 \cdot \exp\left(\frac{c_0}{T_K}\right) \cdot e \tag{28}$$

$$\beta = b_0 \cdot \exp\left(\frac{c_0}{T_K}\right) \cdot v^{-p} \tag{29}$$

In relation (27), x_{PSF} – x* is the gap between the fiber saturation point and the equilibrium moisture content at the temperature T. According to the many authors such as Lartigue and Puiggali (1987) or Nadler et al. (1985), when z tends to 1 (so RH tends to 0 %), x* tends to a low but positive value (about 1 %) so that the ratio z / (x_{PSF} – x*) is defined when T is lower than the water desorption temperature (about 103 °C at 1 atm). The limit of validity of equation (27) is reached when z is very closed from 0 (so when RH tends to 100 %) even if some authors such as Babiak and Kudela (1995) underline that the fiber saturation point can hardly be defined as the value of x* at RH = 100 %.
Consequently, the overall mass-transfer coefficient K can be expressed in general, according to the operating parameters, as:

$$\frac{1}{K} = a_0 \cdot \exp\left(\frac{c_0}{T_K}\right) \cdot e + b_0 \cdot \exp\left(\frac{c_0}{T_K}\right) \cdot v^{-n} \cdot \exp\left[\frac{(RH - 1)}{(\bar{x}_{FSP} - x^*)}\right] \tag{30}$$

In the equation 30, RH is the relative humidity of kiln drying and $\bar{x}_{FSP}$ is the wood moisture content at the fiber saturation point, taken equal to 0.3.
If the exponent n is maintained at 0.8, then the three coefficients in equation 30, a_0, b_0 and c_0 are determined by optimization from the calculated values of the overall mass-transfer coefficients by minimizing the relative error function between the optimized values and the calculated values obtained with equation 30. The values of these three coefficients obtained for optimization are: a_0= 0.12 (m.s.kg^{-1}), b_0= 23.9 (m².kg^{-1}) and c_0= 2683 (K).
Fig 2 compares the calculated values and the optimized values for the overall mass-transfer coefficient. Equation 30 represents all the experimental determinations with an average relative error equal at 15.3 % (and a standard deviation equals at 11 %). This correlation is

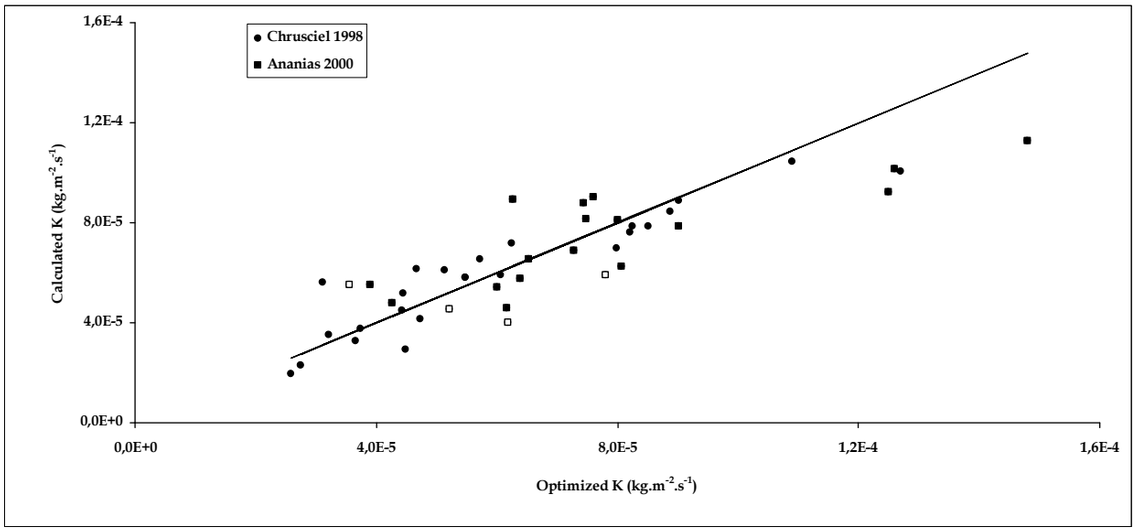


Fig. 2. Comparison of the optimized and calculated values of overall mass transfer coefficient (After Ananias et al. 2009a)

valid for two kinds of lumber studied (spruce and beech), and is satisfactory for a whole kiln-drying schedule.

3. Mathematical model

The model states that the drying rate is a linear function of the drying potential, the moisture-content difference ($\overline{x}$ -x*), and a constant coefficient of proportionality, which is the overall mass-transfer coefficient. This hypothesis has been verified in a previous study (Ananías et al. 2009a).

The model further assumes that the mass and enthalpy transfer takes place unidirectionally, the initial moisture content is homogenous, and the air distribution through the stack is uniform. Heat losses and temperature changes throughout the stack are considered negligible. The model requires the initial values of moisture content and temperature for each sub-system (wood and air) to be known, as well as the overall mass (*K*) and heat-transfer (*h*) coefficients.

The model equations (Karabagli et al. 1997) are from the mass balance of water in drying air,

$$G.(W_{out} - W_{in}) = K.A.(\overline{x} - x^*) \tag{31}$$

the mass balance of water in the wood,

$$-M_0.\frac{d\overline{x}}{dt} = K.A.(\overline{x} - x^*) \tag{32}$$

the enthalpy balance over the drying air,

$$G.\left[\begin{matrix}\left\{C_{pa}.T_{out} + W_{out}.(\Delta h_o + C_{pV}.T_{out})\right\} - \\ \left\{C_{pa}.T_{in} + W_{in}.(\Delta h_o + C_{pV}.T_{in})\right\}\end{matrix}\right] = \\ K.A.\Delta h_V.(\overline{x} - x^*) - h.A.(T - T_w) \tag{33}$$

and the enthalpy balance for the wood,

$$M_0 \cdot \left(C_{pS} + C_{pL} \cdot \bar{x}\right) \cdot \frac{dT_W}{dt} = -G \cdot \begin{bmatrix} C_{pa} \cdot (T_{out} - T_{in}) - (C_{pL} \cdot T_W) \cdot (W_{out} - W_{in}) + \\ C_{pv} \cdot (W_{out} \cdot T_{out} - W_{in} \cdot T_{in}) \\ -\Delta h_0 \cdot (W_{out} - W_{in}) \end{bmatrix} \quad (34)$$

The four equations have been solved as an initial-value problem in a previous study (Ananias et al. 2001, Broche et al. 2002). If equation 32 is solved by means of a finite-difference method, then we can calculate the theoretical wood moisture content at any time ($\bar{x}^{j+1}$). In rearranging this equation, the following relation is obtained:

$$k = -\frac{d\bar{x}}{(\bar{x} - x^*)} \quad (35)$$

On making the transient terms discrete, the following equation is found:

$$k = -\frac{\bar{x}^{j+1} - \bar{x}^j}{\frac{\bar{x}^{j+1} - x^{*j+1} + \bar{x}^j - x^{*j}}{2}} \quad (36)$$

Rearranging this equation to find moisture content at any time ($\bar{x}^{j+1}$), we get:

$$\bar{x}^{j+1} = \frac{(2-k) \cdot \bar{x}^j}{2+k} + \frac{k \cdot (x^{*j} + x^{*j+1})}{2+k} \quad (37)$$

Note that $\bar{x}^j$ and x^{*j} are experimental values and are related to the following error function:

$$E = 100 \cdot \left| \frac{\left(\bar{x}_{exp} - \bar{x}_{cal}\right)}{\bar{x}_{exp}} \right| \quad (38)$$

Finally,

$$K = -\frac{k \cdot M_0}{A \cdot \Delta t} \quad (39)$$

Since the model assumes that coefficient *K* remains constant during drying, it is necessary to dry under constant conditions.

4. Drying curves predictions

We predicted kiln-drying curves, using Spruce (*Picea abies*), Beech (*Fagus sylvatica*) and chilean coigüe (*Nothofagus dombeyi*). The corresponding drying curves are presented in Figures 3-5.

There were minor differences between the experimental and calculated moisture content of the wood. The magnitude of the overall mass-transfer coefficients K is in the range of 0.43×10^{-5} kg/m²s in Chilean coigüe of 38-mm thickness to 12.5×10^{-5} kg/m²s in Spruce of 18-mm thickness (Table 1).

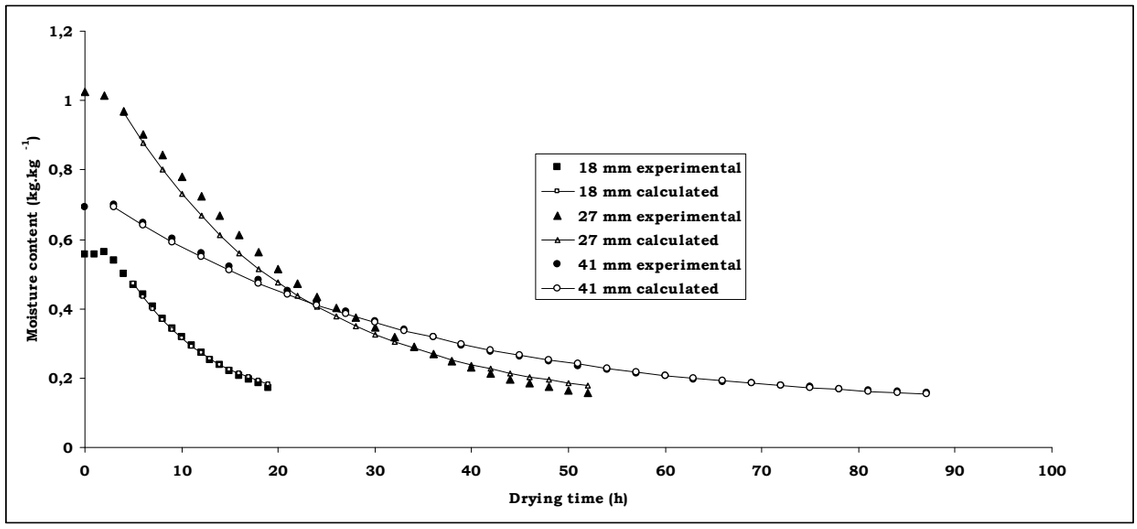


Fig. 3. Kiln drying curves of Spruce wood (After Ananias et al. 2009a)

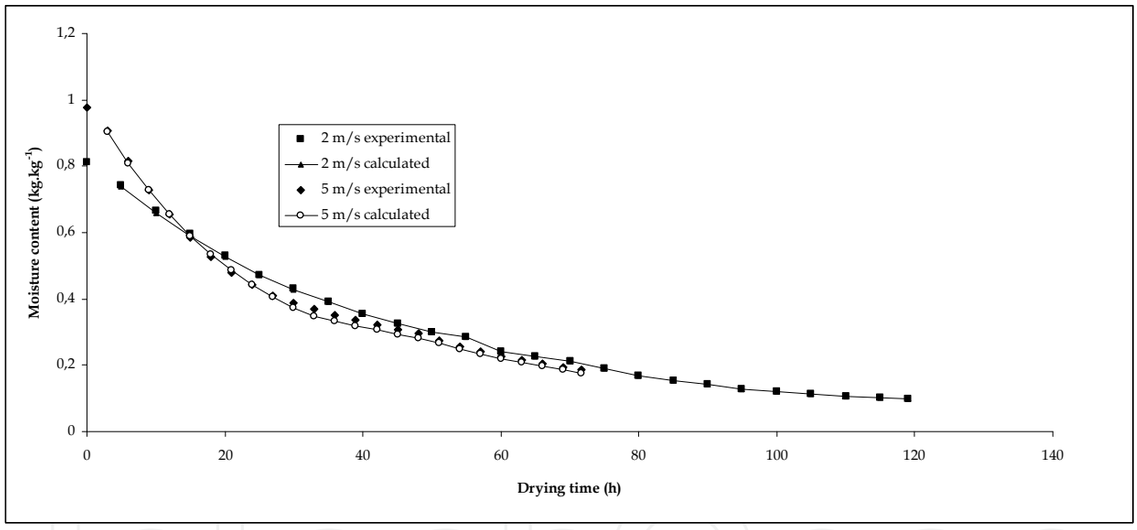


Fig. 4. Kiln drying curves of Beech wood (After Ananias et al 2009a)

Wood Species	**e** (mm)	**T** (°C)	**Tw** (°C)	**v** (m/s)	**K.10^5** (kg/m^2.s)	**Reference**
Spruce	18	70	50	3	12.5	Ananias et al. 2009a
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	Ananias et al. 2009b

Table 1. Overall-mass transfer coefficient

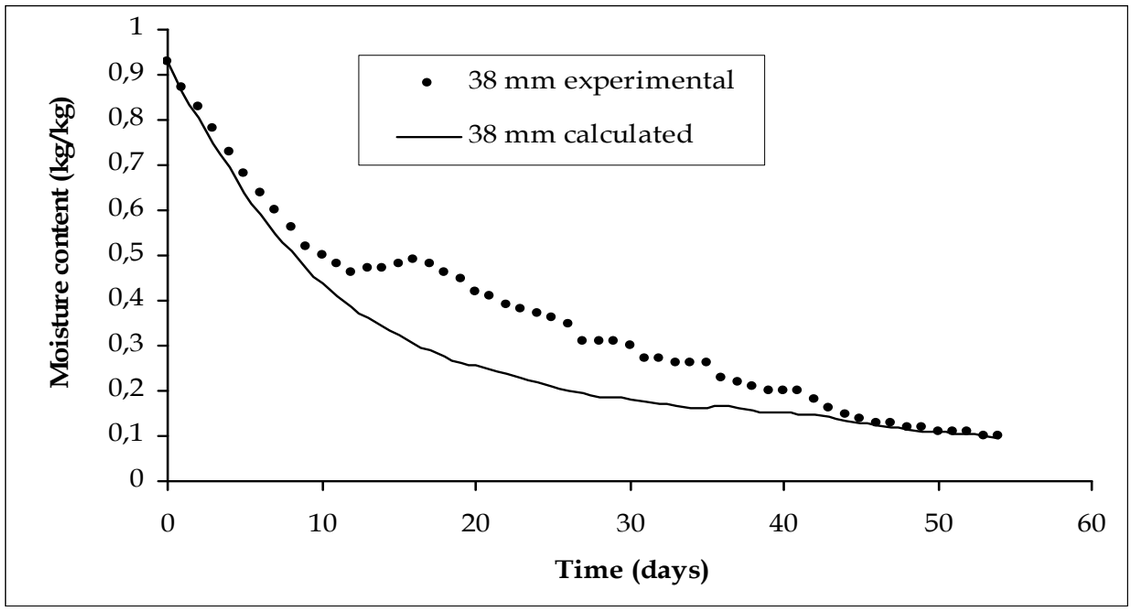


Fig. 5. Kiln drying curve of Chilean coigüe

5. Conclusion

Many low-temperature conventional wood drying curves can be predicted by a constant overall mass-transfer coefficient. The model presented has been tested on different wood drying schedules and the results obtained are very satisfactory. For these reasons, it is suggested that it can be successfully used for drying schedule optimization at industrial scale.

6. List of symbols

A	Transfer surface (m^2)
a	Wood width (m)
a_b	Stickers width (m)
a_o, b_o, c_o, n	Model constants
C_{pa}	Air specific heat (J/kg.^oC)
C_{pL}	Water-Liquid specific heat (J/kg.^oC)
C_{pv}	Water-Vapor specific heat (J/kg.^oC)
d_H	Hydraulic diameter (m)
e	Wood thickness (mm)
G	Air flow rate (kg/s)
H	Specific humidity (kg/kg)
h	Overall heat-transfer coefficient ($W/m^2.K$)
K	Overall mass-transfer coefficient ($kg/m^2.s$)
K_S	Partial mass-transfer coefficient in air-phase ($kg/m^2.s$)
K_g	Partial mass-transfer coefficient in solid-phase ($kg/m^2.s$)
k	Mass-transfer coefficient (non-dimensional)
k_G	Mass-transfer coefficient ($kg/m^2.s.Pa$)
l	Wood length (m)
Mo	Wood dry mass (kg)

Pi	Partial pressure at the interface (Pa)
P_v	Partial pressure (Pa)
P_S	Saturation pressure (Pa)
RH	Relative humidity (kg/kg)
S	Wood surface (m^2)
t	Drying time (h)
T	Air temperature (^oC)
T_K	Air temperature (K)
T_w	Wet-bulb temperature (^oC)
T_{Kw}	Wet-bulb temperature (K)
v	Air velocity (m/s)
W_P	Wetted perimeter (m)
$\bar{x}$	Moisture content (kg/kg)
$\bar{x}_C$	Critical moisture content (kg/kg)
x_i	Initial moisture content (kg/kg)
$\bar{x}_{PSF}$	Fiber saturation point (kg/kg)
x*	Equilibrium moisture content (kg/kg)
z	Residual air dessication ratio [/]
Δh_0	Heat of vaporization at T= 0 ^oC *(J/kg)*
Δh_V	Heat of vaporization *(J/kg)*
Φ	Drying rate [kg/m^2s]
Φ_{MAX}	Maximum drying rate ($kg/m^2.s$)
Φ^+	Reduced drying rate
φ	Non dimensional parameters
u	Air dynamic viscosity (kg/m.s)
υ	Air cinematic viscosity (m^2/s)
ρ	Air density (kg/m^3)
λ	Air thermal conductivity (W/m.K)

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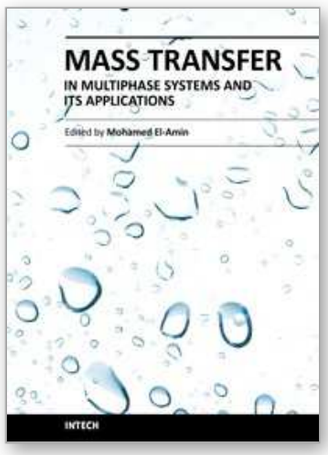
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This book covers a number of developing topics in mass transfer processes in multiphase systems for a variety of applications. The book effectively blends theoretical, numerical, modeling and experimental aspects of mass transfer in multiphase systems that are usually encountered in many research areas such as chemical, reactor, environmental and petroleum engineering. From biological and chemical reactors to paper and wood industry and all the way to thin film, the 31 chapters of this book serve as an important reference for any researcher or engineer working in the field of mass transfer and related topics.

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