USING AN OVERALL MASS-TRANSFER COEFFICIENT FOR PREDICTION OF DRYING OF CHILEAN COIGÜE

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Abstract. A phenomenological model was used to quantify the drying process of Chilean coigüe (*Nothofagus dombeyi*). This model is based on an overall mass-transfer coefficient, *K*, which was determined in four laboratory drying runs. The model suitably described the drying of Chilean coigüe lumber of 19- and 30-mm thickness with K ranging from 0.012 to 0.021 ms^{-1} at a dry-bulb of 60°C and a wet-bulb of 40°C. A preliminary industrial run under somewhat similar conditions in a 100-m^3 industrial kiln with 38-mm-thick lumber showing that the drying process could be represented by a K of 0.008 ms^{-1}. The laboratory-scale values of K can be regarded as ideal from which to compare the performance of the industrial unit.

Keywords: Drying rate, overall mass–transfer coefficient, coigüe, *Nothofagus dombeyi*.

INTRODUCTION

Southern beeches (*Nothofagus* spp.) are notoriously difficult to dry, being impermeable species. However, they are of considerable commercial

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interest because of their decorative qualities. Kauman and Mittak (1964) report on the drying problems with Chilean coigüe (*Nothofagus dombeyi*). They recommend the use of air drying to minimize distortion and reconditioning for recovery of collapse. Currently, the schedule for drying coigüe includes an initial steaming at 70 – 80°C, predrying at 30 – 40°C from green to the FSP, and then final drying in a kiln at conventional temperatures. Even milder schedules are used to dry New Zealand red beech (*Nothofagus fusca*) with the green wood normally being air-dried and the stacked lumber sprinkled with water to avoid excessive drying of the surface. Grace (1996) has shown for another fusca-type beech, *Nothofagus truncata*, that the surface layer of green lumber of such a recalcitrant species can dry very quickly because of the very low permeability of the wood. Unless the initial drying is very gentle, excessive MC gradients are set up, resulting in stresses that degrade the wood. For this reason, intermittent drying, with rest periods enabling the MC distribution through the wood to even, has advantages in restricting the growth of drying stresses (Langrish et al 1992). Such intermittent drying is thought to be one benefit of the successful drying of silver beech (*Nothofagus menziesii*) in a greenhouse-type solar kiln (Langrish and Keey 1992).

If a simple wood-drying model applicable to industrial situations could be found, then there is a possibility of easily monitoring drying performance, reducing drying times and achieving higher quality dried wood. The literature provides many drying models that are based on fundamental transport phenomena as well as phenomenological approaches. The transport models incorporate a greater amount of physical information about the mass and heat-transfer processes than simpler, lumped-parameter models (Perré and Degiovanni 1990; Turner 1996; Perré and Turner 1999). However, the drying of the whole stack is more easily described by an overall phenomenological model (Keey et al 2000; Ananías et al 2001).

One simple phenomenological wood-drying model may be characterized by an overall mass-transfer coefficient, *K*. Such a coefficient includes information about both the internal moisture movement through the wood and well as the mass transfer from the wood surface to the drying air. Consequently, it depends on both the wood characteristics and the drying parameters (Chrusciel et al 1999).

In this work, the drying curves are represented by the model introduced by Karabagli et al (1997). An overall mass-transfer coefficient can be obtained from experimental drying data. This article describes such a drying model as a basis for improving the productivity in drying coigüe.

MATHEMATICAL MODEL

The model states that the drying rate is a linear function of the drying potential, the MC difference (MC – EMC), 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 2009).

The model further assumes that the mass and enthalpy transfer takes place unidirectionally, the initial MC 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 MC and temperature for each subsystem (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:

$$G * (W_{out} - W_{in}) = K * A * \rho_w * (MC - EMC) \tag{1}$$

the mass balance of water in the wood:

$$-M_0 * \frac{dMC}{dt} = K * A * \rho_w * (MC - EMC) \tag{2}$$

the enthalpy balance over the drying air:

$$G * \left[\left\{C_{pa} * T_{out} + W_{out} * (\Delta h_o + C_{pV} * T_{out})\right\} - \left\{C_{pa} * T_{in} + W_{in} * (\Delta h_o + C_{pV} * T_{in})\right\}\right] = K * A * \rho_w * \Delta h_V * (MC - EMC) - h * A * (T - T_w) \quad (3)$$

and the enthalpy balance for the wood:

$$M_0 * \left(C_{pS} + C_{pL} * MC\right) * \frac{dT_W}{dt} = -G * \begin{bmatrix} C_{pa} * (T_{out} - T_{in}) - (C_{pL} * T_W) \\ * (W_{out} - W_{in}) + C_{pv} \\ * (W_{out} * T_{out} - W_{in} * T_{in}) \\ -\Delta h_0 * (W_{out} - W_{in}) \end{bmatrix} \quad (4)$$

The four equations have been solved as an initial-value problem in a previous study (Ananías et al 2001). Only Eq 2 is specific to this work here. If this is solved by means of a finite-difference method, then we can calculate the theoretical wood MC at any time (MC^{j+1}). In rearranging this equation, the following relation is obtained:

$$k = -\frac{dMC}{(MC - EMC)} \quad (5)$$

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

$$k = -\frac{MC^{j+1} - MC^j}{\dfrac{MC^{j+1} - EMC^{j+1} + MC^j - EMC^j}{2}} \quad (6)$$

Rearranging this equation to find MC at any time (MC^{j+1}), we get:

$$MC^{j+1} = \frac{(2-k).MC^j}{2+k} + \frac{k.(EMC^j + EMC^{j+1})}{2+k} \quad (7)$$

Note that MC^j and EMC^j are experimental values and are related to the following error function:

$$E = ABS\frac{\left(MC_{\exp} - MC_{cal}\right)}{MC_{\exp}}100 \quad (8)$$

Finally,

$$K = -\frac{k * M_0 * \rho_w}{A * \Delta t} \quad (9)$$

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

MATERIALS AND METHODS

Materials

The Chilean coigüe used in this study was obtained from a sawmill in the southern region of Chile (Llanquihue). Two sets of specimens were prepared from quartersawn lumber. The first set was for an industrial run and was 38 mm thick, 110 mm wide, and 3.5 m long. The second was for a laboratory study with boards that were 19 or 30 mm thick, 110 mm wide, and 920 mm long that were wrapped in polyethylene film and stored in a shed at ambient temperature. The latter set was prepared from industrial stock that was planed to the two thicknesses to generate fresh surfaces.

Equipment and Procedure

All runs were started with the lumber in the green condition with an end point of about 10% MC.

Laboratory study. A 0.3-m^3 laboratory kiln was used for drying. Temperatures of air and wood were measured at different levels in the stack with thermocouples and the data recorded by computer. The MC of the wood was determined by gravimetric analysis using a balance of 0.01-g precision. The wood was placed in a 10-course stack, 5 boards wide with approximately 10-mm gap and with 25-mm stickers. Four drying runs were carried out with two thicknesses (19 and 30 mm) and two air velocities (1.5 and 3 ms^{-1}). The dry-bulb was fixed at 60°C and the wet-bulb at 40°C. These temperatures correspond to a RH of 30%, giving an EMC of about 4.5% (Siau 1984). MC was determined at regular time intervals using 12 sample boards. The sample size was determined by the statistical procedure described by Broche et al (2002). Before drying, the initial MC was determined by oven-drying. Air was reversed every 4 h. These relatively severe drying conditions were used to illustrate the suitability of the model, not to reflect conditions to produce acceptable quality wood.

Industrial study. A single run with an industrial kiln with a 100-m^3 load of 38-mm-thick wood at temperatures from 40 to 70°C and air velocity 2.5 ms^{-1} was used to compare the performance of an industrial unit with the laboratory runs. The boards were stacked in packages with 20 courses of 10 boards each with 25-mm stickers and approximately 10-mm edge gaps. The kiln load consisted of 30 packages, 3 high, 2 wide, and 5 long. As per standard commercial practice, the lumber was presteamed in the green condition with water-saturated air at 80°C. Twenty sample boards were used to track MC. Air was reversed every 4 h. The dry and wet bulb temperatures were measured with resistance thermometers and recorded by the drying control system. Wood temperature was not directly measured.

RESULTS AND DISCUSSION

The heat-transfer coefficients, *h*, were determined from standard nondimensional correlations for convective transfer. The values, which ranged from 26.7 to 44.1 $Wm^{-2} K^{-1}$, are similar to those reported by Salin (1996) and Pang (1996) for comparable kiln-drying conditions. The transfer coefficients are required for determining the wood temperature (Karabagli et al 1997; Ananías et al 2001).

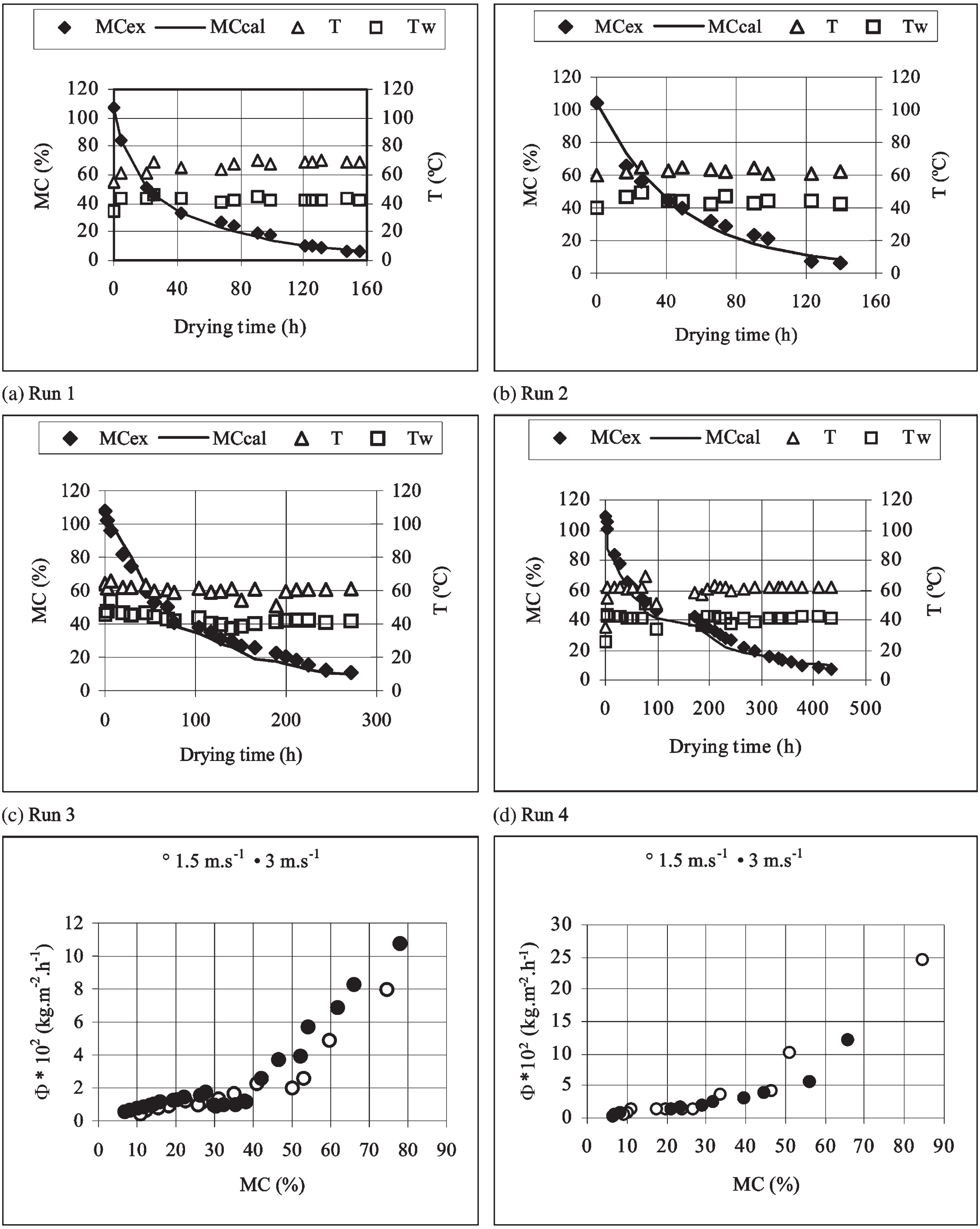
Table 1 shows that the overall mass-transfer coefficients, *K*, for the laboratory drying was in the range 0.012 – 0.021 ms^{-1}. The range is lower than that previously obtained (Karabagli et al 1997; Ananías et al 2009) and is consistent with the slow drying of coigüe. It was observed that K was relatively independent of air velocity, which is expected for an impermeable timber such as coigüe. Figure 1 shows the drying curves for these tests. There were minor differences between the experimental and calculated MC of the wood.

The industrial drying test is shown in Fig 2. Drying could be represented by a single mass-transfer coefficient of 0.08 ms^{-1}, which was obtained by averaging the three linear sections of the drying curve. This is less than the values determined from the small-scale tests (0.012 – 0.021 ms^{-1}). The difference probably reflects the thicker boards (38 mm) used in the industrial kiln as well as airflow variations and the lower temperatures and humidity changes over the more extensive stack of lumber. The calculated mass-transfer coefficient thus represents a potential performance indicator for industrial units in comparison with an "ideal" value obtained in the laboratory.

As expected, thickness was an important variable for such an impermeable species, and the values of K were inversely proportional to thickness of the 19- and 30-mm lumber. The value of Ke was 0.00038 for each (within experimental error), whereas the value for the 38-mm industrial run was 0.00030. Another complexity is the effect of including edges of the lumber in the surface area calculation in that the airflow across the surfaces of edges would be minimal

Table 1. *Operating conditions and overall mass and heat-transfer coefficients.*

	Constants						Variables					
							Initial values				Overall coefficients	
Runs	G	e	A	M_0	T_{in}	W_{in}	MC	T_{out}	W_{out}	T_w	K	h
1	0.3057	0.019	10.6	50.6	65	0.0359	1.08	60	0.0359	42	0.021	33.7
2	0.6116	0.019	11.5	61.1	64	0.0359	1.04	60	0.0359	47	0.020	44.1
3	0.3058	0.030	12.0	83.3	67	0.0530	1.08	58	0.0531	43	0.013	26.7
4	0.6116	0.030	12.4	87.5	66	0.0474	1.08	60	0.0474	40	0.012	37.1
Ind	0.5810	0.038	6800	48750.0	45	0.0514	0.93	42	0.0528	—	0.008	30.8



(a) Run 1

(b) Run 2

(c) Run 3

(d) Run 4

(e) Drying rate for 19-mm boards in run 1 (1.5 $m.s^{-1}$) and 2 (3.0 $m.s^{-1}$)

(f) Drying rate for 30-mm boards in run 1 (1.5 $m.s^{-1}$) and 2 (3.0 $m.s^{-1}$)

Figure 1. Laboratory drying curves of Chilean coigüe (*Nothofagus dombeyi*).

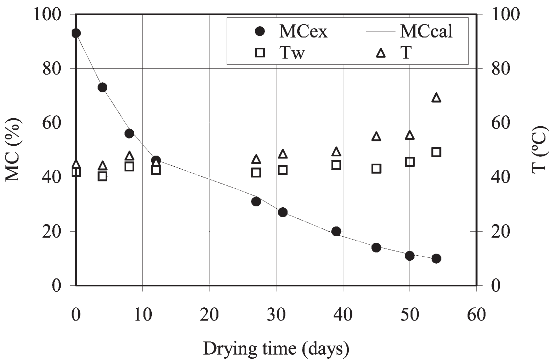


Figure 2. Industrial drying curves of Chilean coigüe (*Nothofagus dombeyi*).

and the contribution of edges to moisture transport increases with increased thickness.

CONCLUSIONS

The kiln-drying of Chilean coigüe at conventional temperatures may be described by a constant overall mass-transfer coefficient for much of the drying process. The value of the overall mass-transfer coefficient may be used to compare the relative drying performance of small-scale and larger kilns under the same nominal schedule. Variations of the coefficients with time could also be an indicator of any drift in performance of a kiln and thus be a benchmarking tool for industrial practice.

LIST OF SYMBOLS

A	Transfer surface between wood and air (m^2)
C_{pa}	Air specific heat ($Jkg^{-1}.°C^{-1}$)
C_{pL}	Liquid specific heat ($Jkg^{-1}.°C^{-1}$)
C_{pv}	Vapor specific heat ($Jkg^{-1}.°C^{-1}$)
e	Wood thickness (m)
E	Error function (%)
EMC	Equilibrium moisture content ($kg_{water}\ kg^{-1}_{oven\text{-}dry\ wood}$)
G	Mass-flow rate of drying air ($kg_{air}\ s^{-1}$)
h	Heat-transfer coefficient ($wm^{-2}\ K^{-1}$)
k	Mass-transfer coefficient (non-dimensional)
K	Mass-transfer coefficient ($m\ s^{-1}$)
M_0	Wood mass ($kg_{oven\text{-}dry\ wood}$)
MC	Wood moisture content ($kg_{water}kg^{-1}_{oven\text{-}dry\ wood}$)
t	Time (h)
T	Dry-bulb temperature (°C)
T_w	Wet-bulb temperature (°C)
T_{in}	Air temperature at stack input (°C)
T_{out}	Air temperature at stack output (°C)
T_W	Average wood temperature (°C)
W_{in}	Absolute air humidity at stack inlet ($kg_{water\ vapor}\ kg^{-1}_{dry\ air}$)
W_{out}	Absolute air humidity at stack outlet ($kg_{water\ vapor}\ kg^{-1}_{dry\ air}$)
Δh_0	Heat of vaporization at T = 0°C (Jkg^{-1})
Δh_V	Heat of vaporization (Jkg^{-1})
Φ	Drying flux ($kg_{water}\ .\ m^{-2}h^{-1}$)
ρ_w	Dry-wood density ($kg\ m^{-3}$)

Subscripts

cal	Calculated
ex	Experimental
j; j + 1	Iterative variable

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