Modeling the Air-drying Rate of Chinese Larch Lumber

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To help protect the environment and reduce energy consumption in the wood industry, air-drying has been used to pre-dry lumber to about 30% moisture content. An air-drying model based on the principle of diffusivity was developed to help estimate air-drying times more accurately. Because the moisture movement rate considerably differs from that which occurs during kiln drying, the effective diffusion coefficients were experimentally determined at different temperatures. A user-friendly computer program predicting air-drying times was developed using the control volume method. The model was experimentally confirmed by air-drying practices. This program is a powerful tool used to estimate the air-drying times for any final moisture content for larch lumber, at any time of the year, at any location where the historical meteorological data, such as temperature, relative humidity, and wind speed, is available. This tool enables mill managers to generate an optimal operation plan based on their kiln capacity, yard availability, inventory requirements, and weather conditions.

Keywords: Air-drying of larch; Effective diffusion coefficients; Estimation of drying times; Modeling

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INTRODUCTION

To reduce energy consumption and protect the environment, air-drying has been used to pre-dry lumber down to a moisture content of about 30%. Air-drying times are affected significantly by the season, the timber size and species, and year-to-year climate variations. Many variables are involved in air-drying, such as the lumber property and the weather conditions, which make estimating air-drying times difficult. Rietz and Page (1971) developed tables to estimate approximate air-drying times for one-inch-thick hardwood and softwood species in specific locations. Rietz (1972) divided the eastern United States into five zones using an air-drying map to estimate the length of effective air-drying conditions. McMillen and Wengert (1978) also tabulated air-drying times for most of the hardwood species dried in the South, Mid-South, Central, and Mid-North. Denig and Wengert (1982) developed the regression equation to estimate daily moisture content (MC), loss from the initial MC, temperature, and relative humidity (RH) data for red oak and yellow poplar. Simpson and Wang (2003) air-dried ponderosa pine and Douglas-fir debarked logs that were stacked at four different times during the year. These data were used to develop multiple linear and nonlinear regression equations. Cai and Oliveira (2012) used a multiple regression model to estimate the drying rates for green spruce/pine dimension lumber. Data analysis revealed that the wind direction did not have a significant effect on the rate of moisture loss.

The computer drying simulation program developed by Hart (1981) can be used to estimate air-drying times with an interpolation method for the months when no experiments were conducted. This computer simulation generally requires a trial-and-error approach to obtain an estimated diffusion coefficient based on the previous drying data. Resch *et al.* (1989) applied Hart's model to the dry Douglas-fir lumber and concluded that the model was a useful tool for lumber drying research and for lumber drying schedule development. Simpson and Hart (2001) used this model to estimate air-drying times for specific locations by optimizing a drying simulation with the existing experimental air-drying times for northern red oak, sugar maple, American beech, yellow-poplar, ponderosa pine, and Douglas-fir. The use of simulation parameters, such as the diffusion coefficient, relative activation energy, *etc.*, resulted in the optimization of the air-drying times of these species. Although the computer drying simulation provided good estimates of the air-drying times for lumber, it was difficult to obtain the simulation parameters from the experimental data (Simpson and Wang 2003).

In fact, limited studies to date have shown the modeling of the air-drying method. Herritsch and Nijdam (2009) developed a drying model that includes both the temperature and MC effects on the diffusion coefficient for highly impermeable hardwoods. Using Matlab 7.0, the coupled partial-differential equations were solved. In their later work (Herritsch and Nijdam 2012), drying-time variations at different locations in New Zealand were investigated using the validated drying model. In addition, an alternative method of drying red beech timber, known as warehouse pre-drying, was simulated using the model.

Keey *et al.* (2000) proposed the following expression for the diffusion coefficient, which includes both the temperature and moisture content effects,

$$D = D_R exp\left[b \cdot MC + \frac{D_e}{T}\right] \tag{1}$$

where D_R is the reference diffusion coefficient, MC is the moisture content, T is the absolute temperature, b is a constant to account for the moisture content effect, and D_e is the activation energy of diffusion. This calculation presents a likely range of values for the activation energy in the temperature term, but provide no values for the constant b, due to a lack of information in the literature on the effect of moisture content on the diffusion coefficient above the fiber saturation point.

Chinese larch (*Larix potaninii*) is an impermeable lumber indigenous species and has the potential to become a significant resource of sustainable timber in China because it is easily planted in the Northern China Mountains, and has good mechanical properties and rot resistance. In this work, a model was developed for predicting the Chinese larch air-drying rate. This is a first step towards optimizing a drying strategy for producing high quality uniformly dried timber in a reasonable time. The developed air-drying model was validated over a range of air-drying conditions by comparing the model predictions with the experimental drying data for Chinese larch lumber.

EXPERIMENTAL

Materials and Methods

As specimens in this study, the green Chinese larch (*Larix*) lumber with a size of 5-cm (thickness) × 10-cm (width) × 240-cm (length) was obtained from a sawmill located in Heilongjiang Province, China. The specimens were block piled to minimize moisture loss during transportation and storage. The air-drying experiments were carried out in Harbin City, Heilongjiang Province, China. The general experimental plan was to stack the larch lumber for air-drying (Fig.1). With the oven-dry method, the individual initial MC was determined using 25-cm discs that were cut from each end of the original 300-cm-long lumber resulting in 240-cm-long specimens.

To obtain accurate weather information during the air-drying, a battery-powered weather station with a data logger (PC-3 Movable Weather Station, Jian Zhou Yanggang Weather Equipment Co., Jianzhou, China) was mounted near the lumber drying stacks as shown in Fig. 1. The weather station was pre-set to measure the temperature, relative humidity, and wind speed every 60 min and store the information along with the time and date. When air-drying was complete, the weather data was exported to a computer.

Two lumber stacks were set up for the air-drying experiments from April to August and from July to October, 2013. The stacks were covered with plywood to protect the lumber from rain and direct sun exposure. Similar to the weather station, the data logger of the load beams was pre-set to record the stack weights every 60 min. After air-drying was complete, the MC loss was calculated for each time interval by using the measured weights during the air-drying and the initial lumber weights and MC.

Fig. 1. Lumber stack, weather station, and load beams

Determination of Effective Diffusion Coefficients

Although it is commonly acknowledged that capillary forces are responsible for the movement of free water and that diffusion is associated with the movement of bound water that occurs below the fiber saturation point (FSP), a diffusive model was utilized in this simulation for both the MC above and below the FSP. The rationale is that the drying rate is likely controlled by moisture diffusion through wood shells, where the MC is below the FSP. The Fickian approach was attractive for the modelling due to its simplicity and ease of numerical solution (Herritsch and Nijdam 2009). Therefore, the diffusive model is suitable for describing the moisture transfer from inside to outside the board. The key element in this simulation is to determine the diffusion coefficient, which depends on the moisture content of the wood.

The air-drying process was conducted at low temperatures, mostly lower than 30 °C, in Harbin, China. The drying rate considerably differed from that of kiln drying. Therefore, the effective diffusion coefficients that directly influenced mass transfer during the air-drying process were determined.

Specimens were cut from larch lumber (flat-sawn sapwood) with a size of 50 mm (width) × 10 mm (thickness) × 100 mm (length) and prepared for the determination of the effective diffusion coefficient (D_{eff}). Thirty replicates were used for each temperature level. All specimens were free from any visual defects and edge-coated with two layers of epoxy resin to prevent moisture loss from the longitudinal and transverse directions during drying.

A conditioning chamber with the temperature and relative humidity kept constant to ± 1 °C and ± 2% of the experimental targets was used. Under a relative humidity of about 50%, drying (desorption) experiments were carried out at six dry-bulb temperatures, namely, 5 °C, 10 °C, 15 °C, 20 °C, 25 °C, and 30 °C. To minimize the effect of surface resistance on the diffusion coefficient, a high air velocity of about 5 m/s was pre-set for the chamber. A digital balance sensitive to 0.1 mg was used to monitor the mass change of the specimens during desorption.

The initial MC of the specimens ranged from 75% to 92% for larch (Table 1). During desorption, the mass of each specimen was monitored with a digital balance. Upon reaching an equilibrium of MC, the specimens were subsequently dried at 103 ± 2 °C to a constant mass. Using the oven-dry mass, the initial MC and moisture loss during desorption was estimated. Assuming the diffusion coefficient is independent of the MC, the following equation (Siau 1984) was used,

$$D = \frac{705.88 \times (\overline{E})^2 L^2}{t} \tag{2}$$

where D is the diffusion coefficient, mm^2/h, L is the half thickness in the moisture diffusion direction, in mm, t is the time, in h, and $\overline{E}$ is the fractional change in the average MC at time t, calculated as follows,

$$\overline{E} = \frac{\overline{C} - C_e}{C_0 - C_e} \tag{3}$$

where $\overline{C}$ is the moisture concentration at time t, in kg/m^3, Ce is the moisture concentration in equilibrium with the water vapor pressure in the surrounding air, in kg/m^3, and C_0 is the initial moisture concentration, in kg/m^3.

Equation 2 indicates that a plot of $\overline{E}^2$ versus t is linear with a slope of D/705.88L^2, so D can be calculated from the slope of a linear regression fitted to the experimental data, as follows,

$$D = 705.88L^2 \times \text{Slope} \tag{4}$$

where $Slope = \frac{(\overline{E})^2}{t}$

Simulation of Air-drying

Assuming that the drying rate is proportional to the moisture gradient, a more correct term used to simulate the air-drying process would be an effective diffusion coefficient (D_{eff}), instead of a traditional diffusion coefficient. The D_{eff} value was determined experimentally through the entire MC range, both above and below the FSP, in the specimens as described in the previous section. D_{eff} values ranged from 0.1 × 10^{-10} m^2/s to 1 × 10^{-10} m^2/s, which agreed with the values in Table 2.

For the larch specimens, the length of 240 cm was much greater than the width (10 cm) and thickness (5 cm), so a two-dimensional approach was used to simulate the heat and mass transfer. The governing equation used for the conservation of energy was as follows (Cai and Oliveira 2008),

$$\rho_{wood} C_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}(k_x \frac{\partial T}{\partial x}) + \frac{\partial}{\partial y}(k_y \frac{\partial T}{\partial y}) + \dot{q}_G \tag{5}$$

where T is the temperature, in K, k_x and k_y are the thermal conductivity in x and y coordinate directions, in W/mK, $\dot{q}_G$ is the rate of heat generation per unit volume, in W/m^3, ρ_{wood} is the basic density of the wood, in kg/m^3, and C_p is the specific heat of the wood, in J/kgK.

Table 1. Parameters Used in the Air-Drying Model

Parameter	Expression
ρ_{wood} (kg/m^3)	The wood basic density = 442 to 510 kg/m^3
C_p (J/kgK)	The specific heat of wood as a function of moisture content (***MC***) can be expressed as follows [Nijdam *et al.* 2000] $C_p = \frac{(0.219+MC)^{0.781}}{1+MC}[8.5(T-273.15)+5300]$ where MC is the lumber moisture content, kg/kg; *T* is the temperature, K
k (W/mK)	The transverse thermal conductivity [Nijdam *et al.* 2000]: $k = \frac{(0.26+MC)^{0.95}}{1+MC}[0.0035M(T-273.15)+0.53]\left[1.7\frac{\rho_{wood}}{1000}0.16\right]$ where MC is the moisture content of lumber, in kg/kg; *T* is the temperature, in K, ρ_{wood} is the basic density of wood, kg/m^3
D_{eff} (m^2/s)	The effective diffusion coefficient varies with temperature (Eq.10)
MC_0 (%)	Initial moisture content = 75 to 92%
h (W/m^{2}K)	The heat transfer coefficient = 4.8 to 9.6 W/m^{2}K [Pordage and Langrish 1999]
h_{ig} (J/kg)	The latent heat of vaporization = 2390 J/kg
h_m (m/s)	The mass transfer coefficient, m/s (Eq. 9)
ρ_g (kg/m^3)	The density of the bulk gas = 0.995 kg/m^3
C_{pg} (J/kgK)	The specific heat capacity of the bulk gas = 1009 J/kgK
Pr	The Pradtl number = 0.7
Sc	Schmidt number = 0.78 [Pordage and Langrish 1999]
v (m/s)	The air velocity

The boundary condition for Eq. 5 can be described by,

$$-k\frac{\partial T}{\partial n}\Big|_r = h\ (T_s - T_\infty)\Big|_r + h_{ig}\,\dot{m}\Big|_r \tag{6}$$

where h is the heat transfer coefficient, in W/m^{2}K, T_s is the surface temperature, in K, T_∞ is the environment temperature, in K, h_{ig} is the latent heat of vaporization, in J/kg, and m is the moisture flux, in kg/m^{2}s.

The governing equation for the conservation of mass is as follows,

$$\frac{\partial M}{\partial t} = \frac{\partial}{\partial x}(D_{eff}\frac{\partial M}{\partial x}) + \frac{\partial}{\partial y}(D_{eff}\frac{\partial M}{\partial y}) \tag{7}$$

where M is the moisture concentration, in kg/m^3, D_{eff} is the effective diffusion coefficient in x and y coordinate directions, $\times 10^{-9}$m^2/s.

The boundary condition for mass transfer is described by,

$$-D_{eff}\frac{\partial M}{\partial n}\Big|_r = \varepsilon h_m(M_s - M_\infty)\Big|_r \tag{8}$$

where M_s is the moisture concentration in wood surface, in kg/m^3, M_∞ is the moisture concentration in the air, in kg/m^3, h_m is the mass transfer coefficient, in m/s, and ε is the correction factor that depends on the M of the surface layer (Cai 2005). The mass transfer coefficient h_m is a function of the air velocity and the heat transfer coefficient.

Because h_m is a function of the air velocity v and the heat transfer coefficient h, they may be related by the Chilton-Colburn analogy (Pordage and Langrish 1999),

$$h_m = \frac{h}{\rho_g C_{pg}}\left(\frac{\mathrm{Pr}}{Sc}\right)^{\frac{2}{3}} \tag{9}$$

where ρ_g is the density of the bulk gas, in kg/m^3, C_{pg} is the specific heat capacity of the bulk gas, in J/kgK, Pr is the Pradtl number, and Sc is the Schmidt number.

The coupled partial-differential equations in Eqs. 5 and 7 were solved using the control volume method (Kreith and Bohn 2001). A control volume is a fixed region in space bounded by a control surface through which heat and mass pass. Using this method, the heat and mass transfer process during the wet-pocket lumber drying was successfully simulated by Cai and Oliveira (2008).

RESULTS AND DISCUSSION

Diffusion Coefficients

Diffusion coefficients of the Chinese larch were determined at six temperatures, *i.e.* 5 °C, 10 °C, 15 °C, 20 °C, 25 °C, and 30 °C. The results, which were the average of 30 specimens, are shown in Table 2. After the regression, Eq. 10 was obtained, which can be used to predict the increase in effective diffusion coefficient (D_{eff}) with temperature.

$$D_{eff} = 0.1918 \ln(T) - 0.0889 \quad (R^2 = 0.9922) \tag{10}$$

where D_{eff} is the effective diffusion coefficient, $\times 10^{-10}$ m^2/s and T is the temperature, °C.

Table 2. Effective Diffusion Coefficients at Different Temperatures

Dry-bulb Temperatures (°C)	Relative humidity (%)	Transverse D_{eff} ($\times 10^{-10}$ m^2/s)
5	50	0.21 (0.019)
10	50	0.36 (0.022)
15	50	0.45 (0.031)
20	50	0.48 (0.041)
25	50	0.52 (0.043)
30	50	0.56 (0.039)

- Values in parentheses are standard deviations.

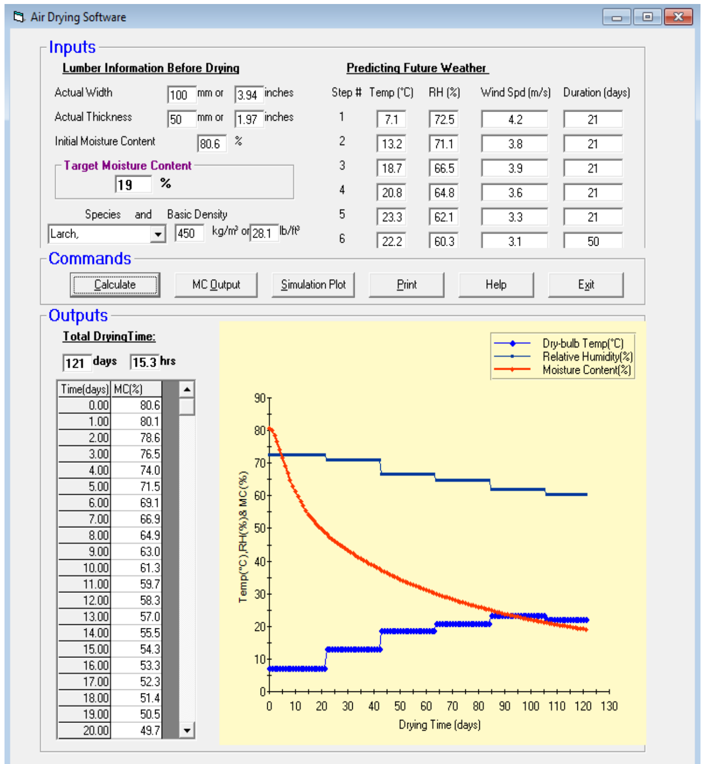

Fig. 2. User interface screen to estimate the air-drying rate (from April to August, 2013)

Simulation Results

Using Visual Basic, the software was developed to predict the air-drying time for larch lumber, and the user interface screens are shown in Fig. 2, from April to August, 2013. The program predicts the MC change over time as a function of initial MC, wood density, lumber dimension, estimated future temperature, relative humidity, and wind speed.

A comparison between the theoretical predicted curve and the data for one lumber stack dated from April to August, 2013 (Run1), is shown in Fig. 3. The data from another lumber stack dated from July to October, 2013 (Run2), together with the curve predicted by the model, is illustrated in Fig. 4. In these two figures, M_{exp} is the experimental results, and M_{calc} is the calculated values based on the model. The differences between the theoretical prediction, the solid lines, and experimental data, the dots, are within an acceptable range in both Figs. 3 and 4, which implies that the air-drying time can be estimated if the historical meteorological data, such as the temperature, relative humidity, and wind speed, is available.

Although no visual difference was observed when comparing the curves in Run 1 (Fig. 3) and Run 2 (Fig. 4), the data analysis showed that the drying rates were different between the two runs, as is apparent from Table 3. Table 3 presents the influence of different initial MC and average temperature on drying rate. The higher drying rate in Run 2 was probably caused by the higher initial MC and higher temperature.

Table 3. A Comparison of Run1 and Run2

Run#	Initial MC (%)	Ave. temperature (°C)	Drying time (days)	Drying rate (%/day)
1	80.6	17.6	123	0.49
2	81.6	18.5	116	0.53

As shown in Fig. 2, the powerful program is capable of predicting air-drying times and provides a tool to take into account the effects of all the variables that affect air-drying time, such as the wood density, initial and target moisture contents, lumber dimensions, temperature, relative humidity, and wind speed. The program is capable of predicting air-drying times to within ± 15% of observed values, as shown in Figs. 3 and 4. Using this tool, a cost-effective mill operation can be achieved by considering the kiln capacity, availability of the air-drying yard, and the inventory requirements.

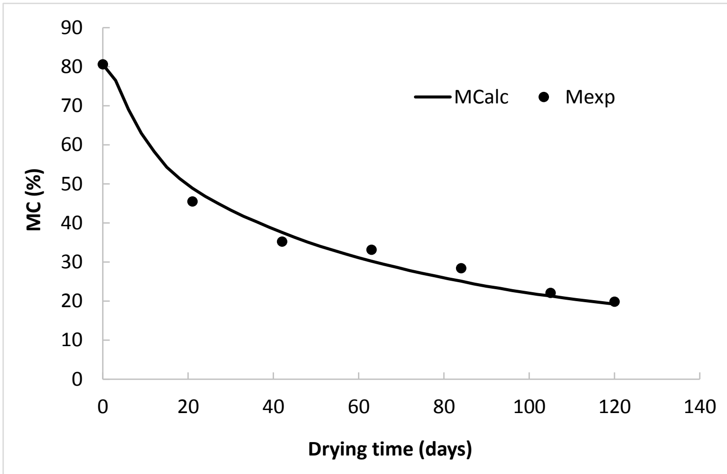

Fig. 3. A comparison between the experimental results (M_{exp}) and calculated curve (M_{calc}) using the software (Run1: from April to August, 2013)

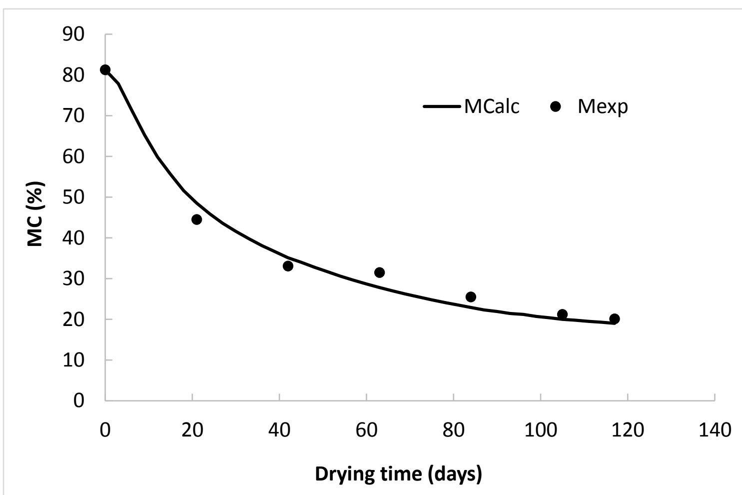

Fig. 4. A comparison between the experimental results (M_{exp}) and calculated curve (M_{calc}) using the software (Run 2: from July to October, 2013)

CONCLUSIONS

1. The effective diffusion coefficient increased with temperature.
2. The experimental validation confirmed that this model is capable of predicting air-drying times to within ± 15% of observed values.

3. The software can estimate air-drying times to any final moisture content, at any time of the year, at any location where the historical meteorological data of temperature, relative humidity, and wind speed, are available.
4. It should be kept in mind that, although the computer program takes into account different variables (*i.e.* density, dimensions) based on the theoretical calculation, only one species (Chinese larch), one dimension (5-cm × 10-cm), and one location (Harbin, China, from April to October) were validated by experiments.

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