

Lumber drying as a diffusion process

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The diffusive character of moisture movement in wood has been investigated by approximating empirical drying schedules as schedules based on diffusion. The diffusivity obtained in this way, checked by drying tests, is discussed on the basis of Eyrings reaction rate theory for diffusion. Schedule parameters have been correlated to wood species properties and physical interpretations on a molecular level with reference to the cell character of wood are discussed tentatively. Criteria were obtained for minimizing of surface checks and for drying defects due to unstable cells.

Holztrocknung als ein Diffusionsvorgang

Der diffusive Charakter der Feuchtigkeitsbewegung bei der Holztrocknung wurde durch näherungsweise Programmierung empirischer Trocknungsprogramme als Diffusionsprogramme untersucht. Die Diffusionszahl, die in dieser Weise erhalten wurde - durch Versuchstrocknungen kontrolliert -, wird auf der Grundlage von Eyrings reaction-rate-Theorie für Diffusion diskutiert. Parameter der Trocknungsprogramme wurden mit Eigenschaften der Holzarten korreliert und physikalische Deutungen auf molekularem Niveau mit Hinweis auf den Zellencharakter des Holzes versuchsweise diskutiert. Kriterien wurden erhalten für die Begrenzung von Oberflächenrissen und Trocknungsschäden auf Grund von instabilen Zellen.

1 Notations

C	constant
D	diffusivity (m^2/s)
E/R	activation energy (K)
s_i/R	activation entropy (-)
R	gas constant for water vapour ($\text{J}/\text{kg}, \text{K}$)
h	heat transfer coefficient ($\text{W}/\text{m}^2, \text{C}$)
m	species parameter (cell stability)
n	diffusivity parameter
r	heat of vaporization (J/kg)
t	dry bulb temperature (C)
t_w	wet bulb temperature (C)
T_w	absolute wet bulb temperature (K)
u	moisture content (kg water/kg dry weight)
u_s	surface moisture content
u_n	natural (green) moisture content
u_*	molecular saturation moisture content
u_c	critical moisture content (=0.24)
u_e	equilibrium moisture content
Δu_n	species parameter (capillary water)
x	lumber thickness coordinate (m)
y	x/δ_1
v	air velocity (m/s)
β	intensity parameter (rad.)
δ_1	half lumber thickness (m)
ρ	density of wood ($\text{kg dry weight}/\text{m}^3$ green volume)

ρ_n	natural mean density
θ	wet bulb depression (C)
τ	drying time (s)
ω	u/u_c

2 Introduction

The thermodynamically irreversible character of the system wood-water, following e.g. from slow irregularities in the time dependence of the moisture content (Malmquist 1966), has the consequence, that physical properties of wood are not exclusively defined by temperature and moisture content. In drying of wood, relevant properties can be expected to be influenced by drying stresses and therefore also by the character of the drying process.

Moisture movement in wood has since a long time (Tuttle 1925) been assumed to have a diffusive character. If so, the diffusivity (diffusion constant) must depend on how the cell walls are strained in drying. As a consequence, the correct diffusivity in a certain process can be experimentally studied with accuracy only by realizing this process.

A comprehensive survey on water diffusion in wood, studied by different authors, is given in a textbook (Siau, 1984). Drying schedules for different species have been tested experimentally to a very great extent, the aim having been to retain the wood quality, the drying time being as short as possible. If such schedules are used in order to check their diffusive character, reproducible values of the diffusivity might be obtained in describing the process. A kiln charge also contains a sufficient number of individuals to define statistical means of its stochastic properties.

European as well as American recommended schedules have been studied in this way in combination to a great number of drying tests (Malmquist 1984, 1988) with the species Scots pine (*Pinus sylvestris*) and whitewood (*Picea abies*), which were performed in a test kiln of capacity 5 m^3 lumber in full length. The weight of the charge was determined continuously and the rate of surface checking was measured.

It was previously shown (Malmquist 1974), that the general formulation of European schedules (Keylwerth 1950) can be deduced as a limiting schedule on the basis of the simple particular solution to the diffusion equation

$$u = C \cos\left(\beta \frac{x}{\delta_1}\right) e^{-D\tau/(\delta_1/\beta)^2} \quad (1)$$

combined with the energy balance in the wood surface (heat accumulation being considered as small). The wet

bulb depression schedule is obtained, if it is assumed, that the wood surface moisture content is in equilibrium with the drying atmosphere. American recommended schedules, given in Dry Kiln Operators Manual (Rasmussen 1961) can be described in a corresponding way, if it is assumed, that the intensified increase of the wet bulb depression in comparison to European schedules has the consequence, that the surface moisture content exceeds the conventional equilibrium value in a certain way, deduced from the schedules.

From this it is obvious, that drying can be treated, at least formally, as a diffusion process. It is of interest, therefore, to investigate which values of the diffusion parameters β and D are compatible with recommended schedules and to perform a more detailed estimation from drying tests of the parameter D in real drying. Physical interpretations of the results obtained in this way are discussed.

The solution (1) can be generalized to

$$u = \sum_{v=1}^3 C_v \cos\left(v\beta \frac{x}{\delta_1}\right) e^{-Dv(\delta_1/v\beta)^2} \quad (2)$$

where C_v can be determined by taking the initial condition of moisture content into account. This solution gives a drying schedule also for the first drying phase, where the conventional schedule prescribes a constant wet bulb depression.

The solutions used are one dimensional for an infinite plate. The drying time for real boards is calculated by taking the increased area of heat transfer by the edges into account. American schedules prescribe a somewhat changing wet bulb temperature with minor rather irregular jumps up and down. A constant value has been used in the calculations, a diffusive schedule then being defined by the two parameters wet bulb temperature t_v and intensity parameter β .

The temperature drop in the drying air, when blowing through a lumber pile, depends on air velocity, sticker thickness and blowing depth in the charge. A sufficient accurate value of the mean wet bulb depression can be calculated for different modes of temperature control and different kiln design.

3 The equilibrium moisture content

From the emc tables, given by Forest Products Laboratory, Madison (Smith 1956), the following relation (Fig. 1) was deduced:

$$100 u_e = \frac{24}{1 + 0.183 \theta} - \left(\frac{\theta}{28}\right)^3 \quad (3a)$$

which shows a practically single valued dependence of the emc (u_e) on the wet bulb depression θ . The formula is correct within a few 0.1% mc in the actual wet bulb temperature range in drying, $t_v = 35-65^\circ\text{C}$, except close to saturation, where the emc increases rapidly towards a conventional fibre saturation moisture content.

In schedule calculations the formula (3a) is simplified to

$$u_e = \frac{0.24}{1 + \theta/5.3} \quad (3b)$$

which gives a moderate error at the highest θ -values used. This formula is assumed to be sufficiently accurate for all species.

By the following discussion the conventional fibre saturation moisture content might be of less value in connection to drying. If it is assumed, that the crystalline part ($\approx 70\%$) of the cell wall has the dry density 1580 kg/m^3 and the total cellwall 1500 kg/m^3 , the amorphous part of the cell wall

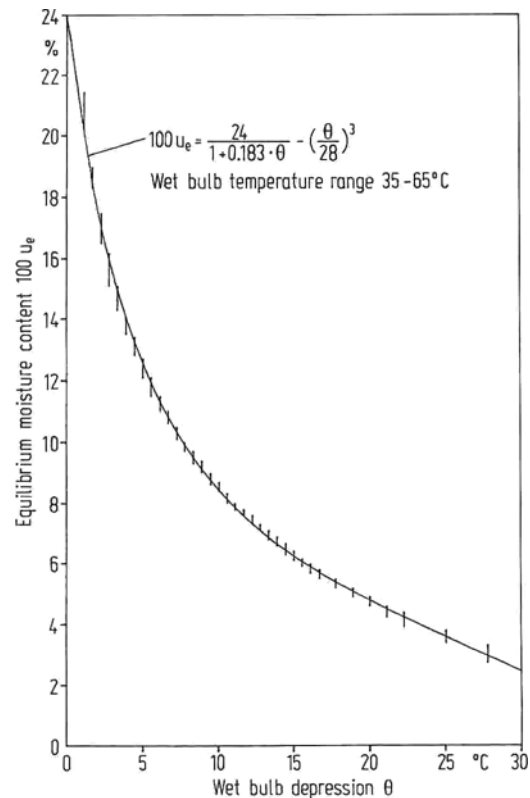


Fig. 1. Equilibrium moisture content as a function of wet bulb depression (θ)

Bild 1. Ausgleichsfeuchte als Funktion der psychrometrischen Differenz (θ)

contains molecular voids, which, when filled with water, correspond to a moisture content $u = 0.11$. If the voids are partly filled with secondary substances (e.g. resins, heart wood substances), the conventional fibre saturation moisture content for different species varies between 0.24 and 0.35. Water in the voids, disappearing close to wet bulb depression zero, is loosely bound and of a similar character as water, which is adsorbed on the lumen surfaces. The moisture content 0.24 therefore seems to be critical in that sense, that below $u_c = 0.24$ appreciable drying stresses can be expected to arise in the presence of a moisture content gradient.

When the moisture content is increased above u_c , filling of the molecular voids and adsorption on lumen surfaces occur simultaneously. The existence may be assumed of a molecular saturation moisture content u_* , where all water active OH-groups in the cell walls are saturated, including secondary hydrogen bonds between water molecules. At higher moisture contents than u_* a formation of capillary menisci are probable as a more stable state. The water film thickness in lumina may become quite large values. Adsorption of water on a glass bulb surface has been measured to give around 200 water molecule diameters thick film (Brunauer 1945). By use of the values of u_* , given below for different species (0.245–1.545), the film thickness can be estimated to the order 0.04–10% of the lumen diameter or 40–9000 water molecule diameters, which seems physically acceptable with reference to the high affinity to water of the cell walls. This saturation moisture content u_* should be proportional to the number of water active OH-groups per kg dry weight of the cell walls. This number may be decreased in different species by cross bound OH-groups in the cellulose and by the presence of secondary substances.

4 Drying phases

The drying process is divided into the following phases:

Phase 1. The first phase ends, when the wood surface moisture content reaches the critical value $u_s = u_c = 0.24$.

Phase 2. The second phase ends, when stress reversal occurs in the wood surface (schematically). According to the American schedule technique the stresses are reversed for *hardwoods* when the wet bulb depression has reached the value $\theta = \theta_{\max} = 28$ C. An equivalent condition is, that the surface moisture content has reached the value

$$u_s = 0.095(1 - e^{-0.7(\beta t_g \beta)^2}).$$

The end of this phase, when drying according to European schedules, is less defined. For *softwoods* the second phase ends, when the mean moisture content has reached the value $u_m = 0.15$ (American and European schedules).

Phase 3. The third phase is defined as final drying with a constant wet bulb depression $\theta = \theta_{\max}$ until the desired end moisture content is reached.

5 The diffusivity

According to the reaction rate theory by Eyring (Glasstone, Laidler, Eyring 1941) the diffusivity is written

$$D = e\lambda^2 \frac{kT}{h} e^{-E/RT + \Delta s/R}, \quad (4)$$

where λ is the distance between two equilibrium positions of a sorbate molecule, k is the Boltzmann constant, h is the Planck constant, E the activation energy and Δs the activation entropy. For self diffusion in water is according to Eyring

$$E/R = 2670 \text{ K}, \quad \lambda^2 e^{\Delta s/R} = 121 \text{ \AA}^2.$$

If it is assumed, that $\lambda \approx 3.5 \text{ \AA}$, we get $\Delta s/R \approx 2.3$. The diffusivity for self diffusion in water then can be written

$$D = 6.87 \cdot 10^{-9} T e^{-E/RT + \Delta s/R} \text{ m}^2/\text{s} \quad (5)$$

where $E/R = 2670$, $\Delta s/R = 2.3$.

This relation may be valid also for diffusion of water in wood, if the diffusion area perpendicular to the grain is reduced in proportion to the dry substance by a factor f_1 and if the diffusion coordinate is increased by a factor f_2 , inversely proportional to the density of wood. The density of the cell wall in the critical state is

$$1/\rho_c = 1/1500 + 0.24/1000, \quad \rho_c = 1100 \text{ kg/m}^3.$$

The factor f_1 (volume of water/volume of cell wall) then is

$$f_1 = \frac{0.24/1000}{1/1100} = 0.264$$

and the factor $f_2 = \rho_c/\rho = 1100/\rho$. From (5) we thus get for wood in the critical state

$$D = 2.00 \cdot 10^{-6} \frac{T}{\rho} e^{-E/RT + \Delta s/R}. \quad (6)$$

According to the cell stability criterion (see below) the activation energy for diffusion in wood is somewhat higher

$$E/R = 2970 \text{ K} \quad (E = 5.89 \text{ kcal/mol})$$

than for self diffusion in water (2670 K). The activation entropy can deviate considerably from $\Delta s/R = 2.3$, depending on how the activated complexes can be realized in the cell walls.

At lower moisture contents $u < 0.24$ the factor f_1 should be

$$f_1 = 0.264 \frac{u}{0.24}$$

if shrinkage is free. The diffusivity thus should decrease proportional to the moisture content. In drying, however, the shrinkage in the surface layer, the diffusivity of which determines the drying rate, is prohibited and tension stresses arise. The factor f_1 thus is frozen to the value 0.264, decreasing successively in dependence of how the cell walls are plastically deformed. The tension stresses also influence the activated complexes, which expand by the tension, i.e. the activation entropy is increased.

Such a complex behaviour of the diffusivity can only be studied on the basis of drying tests according to the diffusive drying schedule studied. Tests with the species Scots pine and whitewood were performed at different temperature levels t_v , different intensity parameters β and different lumber thicknesses $2\delta_1$. It was found appropriate to divide the activation entropy into two parts, one part $\Delta s_0/R$ for stressfree shrinkage and one part $\Delta s_1/R$ depending on t_v , β and δ_1

$$\Delta s/R = \Delta s_0/R + \Delta s_1/R.$$

$\Delta s_1/R$ is not a pure entropy quantity, however, it also includes the change of the factor f_1 .

The tests show, that the surface diffusivity does not change to any appreciable extent in the second drying phase, i.e. the reduced decrease by decreasing surface moisture content is compensated by the increase of wood surface temperature at constant wet bulb depression. The following relation was found from the tests

$$\Delta s_1/R = \beta F_w F_\delta, \quad (7)$$

where the functions F_w and F_δ are supposed as transition functions from elastic to very soft material and from lumber thickness zero to very thick material. Normal distribution functions have been used

$$F_w = \phi\left(\frac{70.6 - t_v}{21.6}\right), \quad F_\delta = \phi\left[2.4\left(1 - \frac{0.015}{\delta_1}\right)\right]. \quad (8)$$

The activation entropy for stressfree shrinkage $\Delta s_0/R$ was studied by use of the relation (7) in estimating the diffusivities for 53 American species, the recommended drying schedules being approximated as diffusion schedules, based on the solution (1). Though an estimation only is possible, the relation

$$\Delta s_0/R = \frac{n}{9} \cdot 2.3$$

is probable, where $n = 1, 2, \dots, 8$ for different species and 2.3 is the activation entropy for self diffusion in water. This seems to indicate, that an activated complex in self diffusion contains 9 water molecules and that this number is reduced to a different degree in different wood species. That part of $\Delta s_1/R$, which is entropy, may stepwise correspond to an increased n -value, caused by tension stresses.

The n -value is influenced also by the character of the diffusion schedule. American schedules with intensified increase of the wet bulb depression in the second phase in comparison to European schedules give one unit higher n -value, and for softwoods the sudden increase of the wet bulb depression in the beginning of the third phase gives another increase with one unit.

The diffusivity in the wood surface layer, when drying according to diffusion schedules with a constant wet bulb temperature thus can be written

$$D = 2.00 \cdot 10^{-6} \cdot \frac{T_v}{\varrho} \cdot e^{-2970/T_v + \frac{n}{9} \cdot 2.3 + \beta F_{iv} F_{\delta}} \quad \text{m}^2/\text{s}. \quad (10)$$

In the third drying phase $\beta F_{iv} F_{\delta} = 0$, because tension stresses in the wood surface are no longer present after the reversal of stresses. The relation (10) is valid in drying from the critical state (in phases 2 and 3).

The moisture content as a potential for moisture movement may be interpreted as a potential to saturate the water active OH-groups in the wood. The net movement of activated complexes is in that direction, where the OH-groups are less saturated, i.e. where the moisture content is lower. Assuming the saturation moisture content u_* to have a real physical significance, the moisture movement then is diffusive in the total range below u_* . In drying from a higher moisture content than u_* ($\Delta u_n \neq 0$, see below) capillary forces may be the driving force, but this is for most species a very short period.

The diffusivity in the first drying phase cannot be calculated from the drying tests, because the drying rate is determined exclusively by the wet bulb depression and the heat transfer coefficient in this phase. Because tension stresses are considerably smaller in this phase, the diffusivity should be lower. This may be compensated by a migration of surface bound water through pores in the cell walls. As a rough approximation may be assumed, that the diffusivity equals that in the second phase.

This approximation is not sufficiently accurate in all cases, however. The increased n -value in phase 2 for American schedules should not be used in phase 1. In drying 75 · 150 mm Scots pine according to a complete European diffusion schedule, the value $n = 6$ (sapwood) was found in phase 2, giving no complications when applied also in phase 1. If $n = 6 + 1 = 7$ was used in phase 1 in drying according to a complete American diffusion schedule, the surface checking was increased with a factor 2, while $n = 6$ in phase 1 and $n = 7$ in phase 2 showed the same checking as the European schedule.

The relation (10) is primarily valid, if the wet bulb temperature is held constant. If it is changed, the relation may still be valid. This was found in the case, that the wet bulb temperature was decreased in the final drying according to kiln design. If it is increased in the drying phases 2 and 3, considerably shorter drying times may be obtainable than for conventional schedules. The drying process is accompanied by a successive increase of the number of cross bound OH-groups, increasing the stability of the cells. A further increased thermal activation above the conventional may therefore be possible without negative consequences as to wood quality. A consequence of such schedules may also be an additional increase of the n -value (even shorter drying times). The CVS-schedule (Nassif 1983) is a schedule of such a type. Tests of this type of schedule is going on.

6 American drying schedules

Schedules, which are recommended in Dry Kiln Operators Manual for hardwoods (lumber) and for softwoods (upper grade), have been studied. The schedules are valid for air velocities between 1 and 2 m/s, temperature control on inlet side and reversed air circulation. This means, that the control value of the wet bulb depression is about 1.7 times higher

than the mean value in a lumber pile, 2–2.5 m wide, in the initial step with constant wet bulb depression.

The diffusive wet bulb depression schedule in phase 2 is deduced from (1) and the energy balance in the wood surface, heat accumulation being neglected,

$$h(t - t_s) = -D \varrho \left(\frac{\partial u}{\partial x} \right)_s \cdot r. \quad (11)$$

It can be shown, that the wet bulb temperature is not changed through the flow boundary layer. By use of (3b) the schedule is

$$\theta = \theta_1 \omega_s + 5.3 \left(\frac{1}{\omega_s - \Delta \omega} - 1 \right), \quad (12)$$

where $\omega_s = u_s/0.24$ is a dimensionless surface moisture content, which is connected to the mean moisture content over the board section ω_m according to (1) by

$$\omega_s = \omega_m \cdot \frac{\beta}{\text{tg } \beta}. \quad (13)$$

The parameter

$$\theta_1 = \frac{0.24 D \varrho r \beta \text{tg } \beta}{h \delta_1}, \quad (14)$$

where the heat transfer coefficient $h = 8 \cdot v^{0.67}$ and the heat of vaporization $r = 2.4 \times 10^6$, is equal to the mean wet bulb depression in the lumber pile, when $\omega_s = 1$. The corresponding control value (schedule value) is $\theta'_1 = 1.7 \theta_1$. All American recommended schedules can be approximated as diffusion schedules, if the excess moisture content above the conventional equilibrium value in the surface is

$$\Delta \omega = \frac{C}{\omega_s(1 - \omega_s)} \exp \left[-\frac{1}{1.28} \left(\ln \frac{\omega_s}{1 - \omega_s} - M \right)^2 \right] \\ 16 C = 1 - \exp \left[-9 \left(\frac{\text{tg } \beta}{\beta} - 1 \right)^3 \right] \quad (15)$$

$M = 0$ for hardwoods, $M = 0.4$ for softwoods

which is a logarithmic normal frequency function of ω_s between 0 and 1. When $\beta \rightarrow 0$, $\Delta \omega \rightarrow 0$. For European schedules $\Delta \omega \equiv 0$. The relation (15) is a summary of the difference between American and European schedule systems. In American as well as in European schedules the dimensionless critical moisture content gradient

$$\left[-\left(\frac{\partial \omega}{\partial y} \right)_s \right]_{\omega_s=1} = \beta \text{tg } \beta$$

depends on lumber thickness according to

$$\beta \text{tg } \beta = \beta_0 \text{tg } \beta_0 e^{-(\delta_1/0.055)^2}.$$

By adding a constant, $u_e = u_e(\theta_{\max}) = 0.029$, in the solution (1), the time dependence of the mean moisture content can be estimated in the final drying with constant wet bulb depression.

By comparison of a diffusion schedule with a corresponding recommended schedule, the intensity parameter β and the diffusivity D can be estimated. For each species the parameters can be checked in three ways, schedules for 25–38 mm and for 50 mm board thickness and also by comparing the drying time for 25 mm thick lumber from green to 6% moisture content, the approximate times being listed in the Manual. In Figs. 2 and 3 examples are shown of recommended schedules and estimated diffusion schedules for 25–38 mm yellow birch and for 25 mm Ponderosa pine.

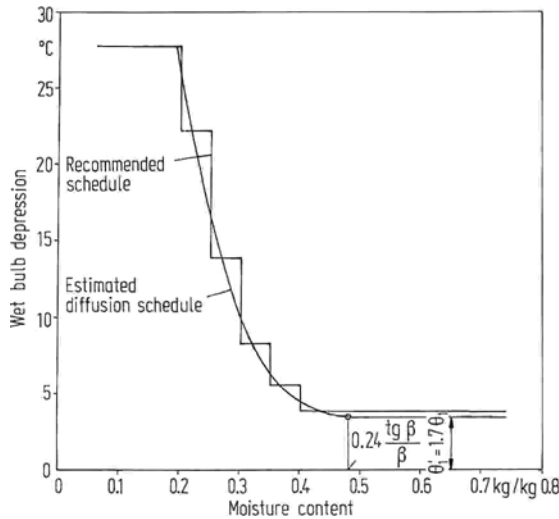


Fig. 2. Wet bulb depression schedule for 25–38 mm yellow birch. $\beta = 1.165$; $t_v = 48^\circ\text{C}$; drying time = 12.7 days (listed 11–15 days)
Bild 2. Trocknungsprogramm für 25–38 mm starkes Birkenholz. $\beta = 1.165$; $t_v = 48^\circ\text{C}$; Trocknungszeit = 12,7 Tage (11–15 Tage)

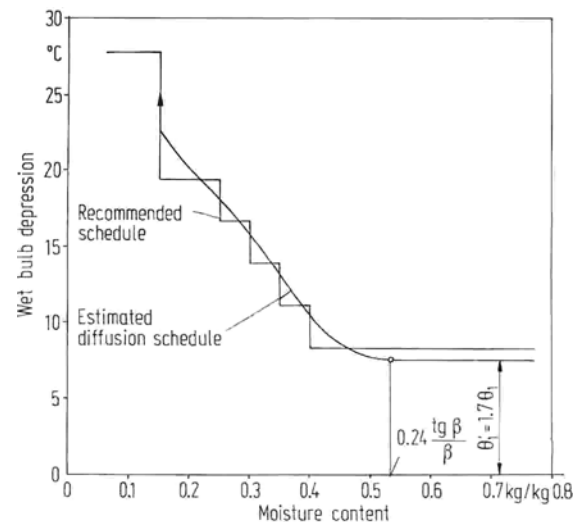


Fig. 3. Wet bulb depression schedule for 25 mm ponderosa pine. $\beta = 1.217$; $t_v = 49^\circ\text{C}$; drying time = 3.9 days (listed 3–6 days)
Bild 3. Trocknungsprogramm für 25 mm starkes Kiefernholz. $\beta = 1.217$; $t_v = 49^\circ\text{C}$; Trocknungszeit = 3,9 Tage (3–6 Tage)

7 Schedule parameters in relation to properties of wood

The parameters t_v and β , which determine a diffusive schedule, have been studied in relation to the species parameters u_n = natural (green) mean moisture content, ρ_n = mean density and shrinkage values to 6% moisture content, given in Dry Kiln Operators Manual. In all, 55 different species have been investigated. In the following possible physical interpretations are discussed for the correlations found.

Drying defects in the wood arise from the drying stresses and their influence on the cells at prevailing temperature and moisture content gradient. This influence may be connected to the species parameters for different values of the schedule parameters. The following correlation coefficients were found:

- u_n $-\beta_0 \text{tg } \beta_0$ $r = 0.88$
- ρ_n $-\beta_0 \text{tg } \beta_0$ $r = 0.50$
- $\rho_n e^{-c/T_v}$ $-\beta_0 \text{tg } \beta_0$ $r = 0.79$
- Shrinkage $-\beta_0 \text{tg } \beta_0$ $r = 0$

An important influence is obvious from u_n and ρ_n , while shrinkage values have no influence on the appropriate moisture content gradient. In the correlations, the critical moisture content gradient $\beta_0 \text{tg } \beta_0$ and the absolute wet bulb temperature T_v have mutually connected values according to the schedules given.

The first correlation indicates very accurately the linear relation

$$\beta_0 \text{tg } \beta_0 = k_1(u_n - \Delta u_n),$$

where the species are divided into five groups with different values of the parameter Δu_n . It is attractive to assume, that $u_n - \Delta u_n = u_*$. This would mean, that the natural moisture content is proportional to the number of water active OH-groups in the cell walls, added by a certain amount of water, if capillary menisci are formed. The critical moisture gradient thus might be proportional to the number of water active OH-groups, i.e. those OH-groups, which are not cross bound or bound to or blocked by secondary substances. The greater the number of water active OH-groups per kg dry weight is, the less is the number of bound OH-groups and the easier are the cell walls strained by the tension stresses, which arise from the prohibited shrinkage in the wood surface layer during drying.

The strain also must depend on the number of thermally activated OH-groups according to the third correlation above. The critical gradient thus might be determined by u_* at an appropriate thermal activation, corresponding to a wet bulb temperature T_v^* . The cell walls then may have a correctly adapted strain to avoid surface checks. On the basis of this view, the proper value of the critical moisture content gradient at the wet bulb temperature T_v^* can be summarized by the *strain criterion*

$$\left. \begin{aligned} \beta_0 \text{tg } \beta_0 &= k_1 u_* & k_1 &= 5 \\ u_* &= u_n - \Delta u_n \\ \Delta u_n &= 0 & \text{for 15 species} \\ &0.075 & 11 \\ &0.15 & 17 \\ &0.3 & 5 \\ &0.6 & 5 \end{aligned} \right\} \quad (16)$$

The value $k_1 = 5$ may be assumed to correspond to an economically acceptable surface checking. If $k_1 < 5$ the rate of surface checking is decreased, but the drying time is increased.

Two species, aspen and basswood, do not obey the strain criterion, Δu_n getting a great negative value (-0.6). This would mean, either that those species grow under a permanent lack of water, or that a great number of checks arise, which are so small, that they have no practical importance. The species have been excluded from a more detailed analysis.

Other drying defects than surface checks (collaps, honey-combing, etc.) arise in dependence of the stability of the cells by other types of stresses during drying. It is natural to assume, that the stability is being decreased by an increasing number of water active OH-groups and also by an increasing number of thermally activated OH-groups. Other factors in the cell design may additionally play a role, as the relative thickness of the cell wall layers, spirality of fibrils, a.s.o.

The concentration c of thermally activated OH-groups in the cells can be written

$$c = k \rho e^{-E/RT_v}.$$

It is reasonable, that an assumed increase du_* of the number of water active OH-groups is connected to a relative

decrease of the concentration c in order to retain a certain stability of the cells, i.e. $-dc/c = k_2 du_*$. Then as stability criterion is obtained

$$qe^{-E/RT_v} = C e^{-k_2 u_*}$$

Maximum correlation coefficient ($r=0.79$) is obtained, when the activation energy is $E/R=2970$ K and the constant $k_2=0.86$. If the investigated species are divided into 5 groups, each for species with an assumed similar cell wall design, the actual data are compatible with the *stability criterion*

$$qe^{-E/RT_v} = e^{-2.85 + m \cdot 0.15 - 0.86 u_*} \tag{17}$$

$m=0$ for 4 species

- 1 15
- 2 21
- 3 8
- 4 5

This relation gives those absolute wet bulb temperatures T_v^* , which agree with recommended values within existing accuracy. When drying with wet bulb temperatures $T_v \neq T_v^*$, the strain criterion (16) is changed into

$$\beta_0 \text{tg} \beta_0 = k_1 u_* e^{-\frac{E}{R} \left(\frac{1}{T_v} - \frac{1}{T_v^*} \right)} \tag{16a}$$

at sufficient cell stability. This relation has been tested by drying the check refractory lumber 75×150 mm Scots pine and whitewood at different wet bulb temperatures and different β -values. A well defined quadratic relation (Fig. 4), was found between the mean relative check area a_s for 98 lumber peaces in full length and the check parameter k_1 . The value 5 corresponds to American recommendations and is also in this case a suitable value of this parameter.

Two kiln charges with prefrozen timber showed about half the check area as compared with the other charges. If, however, it is assumed, that Δu_n is changed from 0.15 to zero by freezing, also prefrozen timber fits in the diagram. This would mean, that a number of OH-bonds in the cellulose is broken in freezing, which corresponds to an increase of u_* by Δu_n , i.e. the capillary water is changed into surface adsorbed water in freezing, the cells not being damaged by freezing.

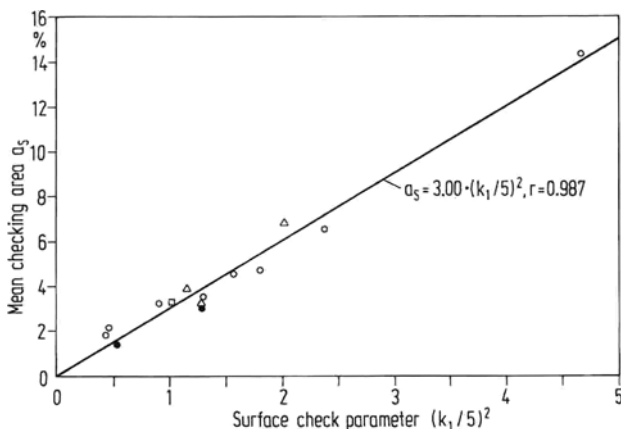


Fig. 4. Measured surface check area (a_s) for 75×150 mm Scots pine (*Pinus sylvestris*) and whitewood (*Picea abies* sp.) as a function of the check parameter k_1 . \circ = *Pinus sylvestris* (E); \bullet = *Pinus sylvestris* (E), prefrozen timber; \square = *Pinus sylvestris* (A); \triangle = spruce (E).

$$a_s = 3.00 \cdot \left(\frac{k_1}{5} \right)^2, r = 0.987$$

Bild 4. Mittlere Rißfläche (a_s) als Funktion des Parameters k_1 für Oberflächenrisse, gemessen an 75×100 mm Proben von Kiefern- und Fichtenholz. $a_s = 3,00 \cdot \left(\frac{k_1}{5} \right)^2, r = 0,987$

Table 1. Species parameters for American species – hardwoods

Species	q_n	u_n	Δu_n	n	m	
Alder, red	370	0.97	s	0.15	2	1
Apple	610	0.81	h	0.3	4	2
Ash, white	550	0.46	h	0	2	2
Beech, American	560	0.55	h	0.075	2	2
Birch, paper	420	0.89	h	0.3	3	1
Birch, yellow	550	0.74	h	0.15	3	2
Cherry, black	470	0.58	h	0.15	2	1
Chestnut, American	400	1.20	h	0.15	2	3
Cottonwood	320	1.62	h	0.075	2	4
Elm, American	460	0.95	h	0.15	3	1
Elm, rock	570	0.44	h	0	2	2
Hackberry	490	0.61	h	0	3	2
Hickory	640	0.72	h	0.15	3	3
Hophornbeam	630	0.52	h	0.15	3	2
Locust, black	660	0.40	h	0.15	3	3
Magnolia	460	0.80	h	0	2	3
Maple, silver	440	0.58	h	0	3	1
Maple, sugar	560	0.65	h	0.15	3	2
Oak, California black	510	0.76	h	0	1	1
Oak, red	540	0.815	h	0.15	2	1
Oak, white	600	0.64	h	0.15	2	2
Persimmon	640	0.58	h	0.075	4	2
Sweetgum, red	460	0.79	h	0.15	1	1
Sweetgum, sap	460	1.37	s	0.6	3	4
Sycamore	460	1.14	h	0.6	3	0
Tupelo, black	460	0.87	h	0.075	2	4
Walnut, black	510	0.90	h	0.075	3	2
Yellow poplar	400	0.83	h	0	2	3

Table 2. Species parameters for American species – softwoods

Species	q_n	u_n	Δu_n	n	m	
Bald cypress	420	1.21	h	0.6	1	4
Cedar, Alaska	420	0.32	h	0.075	4	2
Cedar, eastern red	440	0.33	h	0	4	0
Cedar, Incence	350	0.40	h	0	4	1
Cedar, Port Orford	400	0.50	h	0.15	3	2
Cedar, w. red (heavy)	310	1.20	hs	0.15	1	0
Douglas fir (coast type)	450	0.37	h	0.075	6	2
Fir, grand	370	0.91	h	0	3	3
Fir, noble	350	0.34	h	0	3	1
Fir, Pacific silver	350	0.55	h	0.15	4	1
Fir, white	350	0.98	h	0.075	3	3
Hemlock, eastern	380	0.97	h	0.6	5	2
Hemlock, western	380	0.85	h	0.3	4	2
Larch, western	510	0.54	h	0.15	6	2
Pine, Lodgepole	380	0.41	h	0	5	1
Pine, Ponderosa	380	0.77	hs	0.075	5	1
Pine, red	400	0.655	hs	0.3	3	2
Pine, Loblolly	470	0.60	hs	0	5	4
Pine, sugar (heavy)	350	1.465	hs	0.075	4	2
Pine, western white	360	0.62	h	0.075	5	0
Redwood, old growth	380	1.96	s	0.6	1	2
Spruce, black	380	0.66	hs	0.3	4	1
Spruce, Engelmann	320	0.94	hs	0	3	1
Spruce, sitka	370	0.41	h	0	3	2
Tamarack	490	0.49	h	0.15	5	3

Given and calculated data for American species are summarized in Tables 1 and 2. Heartwood control is denoted by h and sapwood control by s . Some softwoods are controlled on the basis of both heartwood and sapwood (hs), but no details are given in the manual. The geometric mean of green heartwood and sapwood moisture contents has been used in the calculations. The n -values given in the tables are valid for drying phase 2.

Calculated drying times correspond as a mean to the middle of the ranges listed, but two species, paper birch and sycamore, give longer drying times than listed. The quotient between calculated and given initial wet bulb depressions is unity as a mean.

8 The complete diffusion schedule

Considering the moisture movement as diffusive also in the first phase of drying, the time schedule for phases 1 and 2 is based on the solution (2). The wet bulb depression schedule is

$$\theta = \theta_k \left(\frac{\partial \omega}{\partial y} \right)_s + 5.3 \left(\frac{1}{\omega_s - \Delta \omega} - 1 \right) \quad (18)$$

$$\theta_k = \frac{0.24 D q r}{h \delta_1}$$

In the first phase ($\omega_s < 1$) the last term in (18) is zero (surface temperature = wet bulb temperature). ω_s , ω_m and $(\partial \omega / \partial y)_s$ are calculated from (2) as functions of time. In the first phase, where a conventional schedule prescribes a constant wet bulb depression, the complete schedule starts close to zero, increases to a maximum value (if β is not very small) and decreases then towards the critical state.

In the third phase the schedule is $\theta = \theta_{\max}$. The solution (1), adding a constant $u_e = u_e(\theta_{\max})$ is used here, but as the initial condition is not considered otherwise than equal mean moisture content u_{m2} at the transition to the third phase, it has been found appropriate to retain $u_e = 0$ until the mean moisture content reaches the value $u_{m2} - 0.04$.

For Scots pine and whitewood it was found appropriate to control drying on the basis of sapwood in the phases 1 and 2 and on mixed sapwood-heartwood in phase 3. The following species parameters were obtained:

	Scots pine	whitewood		
u_n	1.33 s	1.55 s		
	0.33 h	0.38 h		
Δu_n	0.15 s	0.3 s		
q_n	430	385		
Phase	1	2	3	
n	6	6	6 s	European schedule (E)
			4 h	
n	6	7	8 s	American schedule (A)
			6 h	

A detailed summary of the calculation of a schedule of this type is given in a report (Malmquist 1990).

9 Influence of kiln design on schedules

The control value θ'_k of the parameter θ_k in (18) [or θ'_1 of the parameter θ_1 in (12)] can be calculated according to the following relations:

1. If the temperature control is on inlet side of a pile

$$\theta'_k / \theta_k = \frac{\gamma L}{1 - e^{-\gamma L}}$$

2. If the temperature is controlled as a mean value on inlet and outlet sides of a pile

$$\theta'_k / \theta_k = \frac{\gamma L}{2} \frac{1 + e^{-\gamma L}}{1 - e^{-\gamma L}}$$

3. If the temperature is controlled in the middle of a pile

$$\theta'_k / \theta_k = \frac{\gamma L e^{-\gamma L / 2}}{1 - e^{-\gamma L}}$$

where

$$\gamma = \frac{16}{d_s} v^{-0.33}, \quad d_s = \text{sticker thickness (mm)}$$

$$v = \text{air velocity (m/s)}$$

$$L = \text{depth of pile (m)}$$

The air velocity v should be measured separately for each lumber thickness. The parameter γ may be changed, if the lumber contains both sapwood and heartwood with appreciable different initial moisture contents.

10 Conclusions

A very great number of empirical lumber drying schedules can be transformed into diffusive time schedules. In this way the drying process can be controlled by use of a micro computer and the trouble-some moisture content measurement during drying be omitted.

The state of the free OH-groups and their connection to secondary substances in the cells seem to have an important influence on which drying schedule is to be used in order to retain the wood quality. Two criteria for small drying defects were deduced on this basis.

The diffusive character of moisture movement seems to be dominant. The diffusivity can be calculated by use of Eyrings reaction rate theory, except for the activation entropy, which must be estimated from a known empirical schedule or from drying tests.

The complete diffusion schedule proposed, successively developed on the basis of drying tests with the species Scots pine and whitewood, is probable to correspond to physical reality. It is introduced in the Swedish saw mill industry and is used to an increasing extent since 1981.

11 References

- Brunauer, S. 1945: The adsorption of gases and vapors. Vol. 1. Physical adsorption. Princeton
- Glasstone, S.; Laidler, K.; Eyring, H. 1941: The theory of rate processes. New York, London
- Keylwerth, R. 1950: Das Trocknungsgefälle und die Steuerung von Holz-trockenanlagen. In: Kollmann, F., Keylwerth, R. (Hrsg.) Beiträge zur Kraft- und Wärmewirtschaft in der Holzindustrie 7:56-62
- Malmquist, L. 1966: Untersuchungen zur empirisch-mathematischen Analyse der Sorption von Wasserdampf durch Holz. Diss. München 1966. Kurzfassung. Holz Roh- Werkstoff 25:45-62
- Malmquist, L. 1974: Analysis of modern lumber drying (in Swedish). STFI Medd. B 278
- Malmquist, L. 1984: Compound drying of timber. An analysis of drying defects (in Swedish, summary in English). Swedish Inst. Wood Tech. Res. Report 62
- Malmquist, L. 1988: Kiln drying of lumber on the basis of a diffusion model (in Swedish, summary in English). Swedish Inst. Wood Tech. Res. Report I8902004
- Malmquist, L. 1990: An improved model for kiln drying of lumber (in Swedish). Swedish Inst. Wood Tech. Res. Report I9008043
- Nassif, N.M. 1983: Continuously varying schedule (CVS) - a new technique in wood drying. Wood Sci. Technol. 17:139-144
- Rasmussen, E. 1961: Dry kiln operators manual, Agriculture Handbook nr 188. FPL, US Dept. of Agriculture
- Siau, J.F. 1984: Transport processes in wood. Berlin Heidelberg New York: Springer
- Smith, H. 1956: Relative humidity and equilibrium moisture content graphs and tables for use in kiln drying lumber. FPL, US Dept. of Agriculture
- Tuttle, F. 1925: J. Franklin Inst. p. 609