Criterial assessment of the drying quality

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Abstract

The present paper aims to determine the moisture content distribution of a wood board during drying by numerical modelling and to use a criterion of similarity which is able to describe the moisture content when there is a probability for the surface cracks to occur. The constant-rate drying period will be considered, when the mass transfer intensity is maximum. The system of partial differential equations governing the phenomenon consists in the unsteady energy and mass (moisture) equations and is considered in its 1D version. One way to tackle the problem is to use the analytical solution given by Luikov and the other is to use the numerical simulation performed with Torksim (version 5.0); our strategy is to combine these two ways in order to derive an appropriate hygrometric criterion.

The proposed hygrometric criterion assesses the moisture content distribution of the body, being a measure of the inner stresses magnitude. The criterion is related to the velocity, temperature and relative humidity of the drying agent. They are to be selected in such a way that they can determine, at all times of the drying process, a lower value than the maximum value of the criterion. By use of this method an optimal domain of the drying schedules, with respect to the wood quality, can be recommended, and consequently the drying schedule with the maximum drying intensity can be chosen. In order to obtain the hygrometric criterion from the moisture content distributions, four drying schedules are applied to pine samples.

1 Introduction

The heat and mass transfer that occurs at the surface of wet bodies during convective drying is accompanied by changes in the physical and mechanical properties of the body. These changes may lead to undesired quality defects if inappropriate drying schedules are applied.

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The moisture evaporation in the boundary layer results in a continuous change of the inner moisture content and thus the dimensional change will be different in different layers on the body thickness and at different drying times. Accordingly, tension stresses are developed at the surface and inside the body, which determine cracks if the moisture content drop exceeds a maximum value. Since the absence of cracks is the main requirement of the wood quality during drying, it is necessary to determine the moisture content gradient in the wood board and accordingly to use a criterion of similarity which can assess the moisture profile when there is a risk for the surface cracks development. The main reason for stresses is the moisture gradient and the outcome consists in micro- and macro-cracking.

During lumber drying above fibre saturation point, capillary flow frequently leads to drying defects in various wood species. Drying above FSP has been described as a two-stage process (Keey 1994): in the first stage, the wetline remains close to the surface (at approximately 50% MC – Scheepers *et al.* 2005), in the second stage the wetline starts to move towards the core.

Song & Shida (2010) by examining the effects of the surface temperature on the surface checking using the infrared thermography technique, have obtained a relationship between moisture content and surface checking, with the observation that above the fibre saturation point checking developed as the drying advanced.

The radial, tangential and volumetric shrinkages occur above FSP, behaviour that can be explained by the effect of hysteresis at saturation on wood properties, according to which the loss of bound water takes place in the presence of free water (Almeida *et al.* 2005).

The present paper aims to determine the moisture distribution of the board during drying above fibre saturation point by numerical modelling and to use a similarity criterion which is able to describe the moisture content when there is a probability for the surface cracks to occur.

2 Mathematical model

The temperature and moisture content fields of a body submitted to convective drying can be determined from the solution of the coupled system of differential equations of heat and mass transfer (Luikov 1966):

$$\frac{\partial M}{\partial \tau} = a_m \nabla^2 M + a_m \delta \nabla^2 t \qquad \text{Equation 1}$$

$$\frac{\partial t}{\partial \tau} = a_e \nabla^2 t + k \frac{\partial M}{\partial \tau} \qquad \text{Equation 2}$$

where a_m is the moisture diffusion coefficient, δ - coefficient of thermal diffusion, a_e - coefficient of thermal diffusivity, k - constant coefficient, equal to

$$k = \frac{a_{m1} r}{c} \qquad \text{Equation 3}$$

where a_{m1} is the mass transfer coefficient corresponding to the liquid, r - the latent heat of vaporisation, c - specific heat of the body.

For very long boards of thickness 2R, assuming the symmetry of the heat and mass transfer related to the board sides, the following initial and boundary conditions can be written:

$$M(x,0) = M_0(x) = \overline{M}_0 = const$$
$$t(x,0) = t_0(x) = \bar{t}_0 = const \qquad \text{Equation 4}$$

and

$$\frac{\partial M(0,\tau)}{\partial x} = \frac{\partial t(0,\tau)}{\partial x} = 0 \qquad \text{Equation 5}$$
$$a_m \rho_0 (\nabla M)_s + a_m \rho_0 \delta (\nabla t)_s + J_1(\tau) = 0$$
$$-\lambda (\nabla t)_s + \alpha (t_{air} - t(R,\tau)) - r(1 - a_{m1}) J_1(\tau) = 0$$

where subscript *s* refers to the surface (*x*=*R*), ρ_0 - ovendry density of the body, $J_1(\tau)$ - mass flux per unit area, λ - coefficient of thermal conductivity, α - heat transfer coefficient. If the thermal diffusion is neglected $(\delta = 0)$, then Equations 1 and 5 become:

$$\frac{\partial M}{\partial \tau} = a_m \frac{\partial^2 M(x,\tau)^2}{\partial x^2} \qquad \text{Equation 6}$$

$$a_m \rho_0 \frac{\partial M(R,\tau)}{\partial x} + J_1(\tau) = 0$$

Luikov’s solution of Equation 6 is:

$$\frac{\overline{M} - M(x,\tau)}{\overline{M}_0 - EMC} = \int_0^\tau \frac{J_1(\tau)}{R\rho_0 \overline{M}_0} d\tau - Ki^*(\tau) \frac{R^2 - 3x^2}{6R^2} + \qquad \text{Equation 7}$$
$$\sum_{n=1}^{\infty} (-1)^{n+1} \frac{2}{n^2 \pi^2} \cos \frac{n\pi x}{R} \exp\left(-n^2 \pi^2 \frac{a_m \tau}{R^2}\right) \times$$
$$\left[Ki^*(0) + \int_0^\tau \exp\left(\frac{n^2 \pi^2 a_m \tau}{R^2}\right) \frac{dKi(\tau)}{d\tau} d\tau \right]$$

where $Ki^*(\tau) = \frac{J_1(\tau) R}{a_m \rho_0 \overline{M}_0}$ is the hygrometric Kirpichev similarity criterion (Kirpichev number).

If checking takes place during the constant drying-rate period, when the mass transfer reaches its maximum intensity and is constant during this period of time, meaning that $\frac{dJ_1(\tau)}{d\tau} = 0$, then a constant value of the hygrometric criterion can be assumed $\frac{dKi(\tau)}{d\tau} = 0$. With this assumption, Equation 7 becomes:

$$\frac{\overline{M}_0 - M(x,\tau)}{\overline{M}_0 - EMC} = Ki^* \left[Fo^* - \frac{R^2 - 3x^2}{6R^2} + \sum_{n=1}^{\infty} (-1)^{n+1} \frac{2}{n^2\pi^2} \cos\frac{n\pi x}{R} \exp\left(-n^2\pi^2 Fo^*\right) \right] \qquad \text{Equation 8}$$

where $Fo^* = \frac{a_m \tau}{R^2}$ is the hygrometric Fourier number. The increase of Fourier number, as time elapses, determines the series members from Equation 8 to become rapidly convergent and for values beginning with $Fo \geq 0.54$, they can be neglected with respect to the first two members and thus the solution can be written as (Luikov&Mikhailov 1965):

$$\frac{\overline{M}_0 - M(x,\tau)}{\overline{M}_0 - EMC} = Ki^* \left(Fo^* - \frac{R^2 - 3x^2}{6R^2} \right) \qquad \text{Equation 9}$$

In this case the local moisture content on the board thickness will be a linear time function and its distribution along the board thickness is a parabolic one.

Considering that the surface checking occurs in the first drying period, a criterion can be adopted for describing the moisture content field which is able to develop surface cracks, namely:

$$K = \frac{M(0,\tau) - M(R,\tau)}{\overline{M}_0 - EMC} \qquad \text{Equation 10}$$

where $M(0,\tau)$ and $M(R,\tau)$ correspond to the moisture content in the centre and on the surface of the board, $\overline{M}_0$ - the average initial moisture content, *EMC* – the equilibrium moisture content. Considering Equation 9, the dimensionless criterion *K* will be:

$$K = \frac{M(0,\tau) - M(R,\tau)}{\overline{M}_0 - EMC} = \frac{1}{2} Ki^* \qquad \text{Equation 11}$$

For boards with a symmetric distribution of the moisture content along the thickness, the average moisture content is:

$$\overline{M}(\tau) = \frac{1}{R} \int_0^R M(x,\tau)\,dx \qquad \text{Equation 12}$$

and on using Equation 9, the following relation can be obtained:

$$\overline{M}(\tau) = \overline{M}_0 - (\overline{M}_0 - EMC)Ki^* Fo^* \qquad \text{Equation 13}$$

For constant Ki^*, $\overline{M}(\tau)$ is a linear function of τ. From Equation 13 we have:

$$Ki^* = \frac{d}{dFo^*}\left(\frac{\overline{M}(\tau)}{EMC - \overline{M}_0}\right) = \frac{\overline{M}_0 - \overline{M}(\tau)}{(\overline{M}_0 - EMC)Fo^*} \qquad \text{Equation 14}$$

which can be also written as:

$$Ki^* = \frac{\overline{M}_0 - \overline{M}(\tau)}{(\overline{M}_0 - EMC)Fo^*} = 2\frac{M(0,\tau) - M(R,\tau)}{\overline{M}_0 - EMC} = 2K \qquad \text{Equation 15}$$

Kirpichev number ranges between 0 and 2. A small value determines a small internal resistance to diffusion and vice versa. Equation 15 shows the relationship among the hygrometric criterion and the average board moisture content. The moisture content gradient along the board thickness determines the magnitude of the hygrometric criterion.

The Kirpichev hygrometric number can be used as a criterion for the assessment of the moisture content field on the board thickness in the constant drying rate period, being thus a quantitative measure for the stresses that determine surface cracks. Since the mass flux depends on the drying schedule (velocity, temperature and relative humidity of air), then a relationship between the hygrometric criterion (moisture profile) and the drying air properties can be settled. In order to prevent surface checking, the temperature and relative humidity must be thus chosen so as to get lower values of the hygrometric criterion than the maximum (critical) one that corresponds to the moment when surface cracks occur. By use of this method an optimal domain of the drying schedules, with respect to the wood quality, can be recommended, and thus a drying schedule with the maximum drying intensity can be chosen.

3 Method and material

Pine wood samples with two different initial moisture contents, 130% and 60% and a thickness of 28 mm are submitted to four drying schedules. The first drying schedule is a standard one, tested in practice, as proposed by Seba Industrial Company, whilst the other three ones correspond to constant velocity (3 m/s), temperature (50, 60, 70, 80 ^{o}C) and RH values (60, 50 and 40%). Two methods for the determination of the hygrometric criterion are applied; one is aimed for the calculation of the criterion variation across the board thickness (Eq. 9), while the second one is that of its time dependence with respect to the applied drying schedule (Eq. 15). The moisture content - time variation, average board temperature and moisture content are obtained by use of the wood drying simulation package TORKSIM, version 5.0.

4 Results and discussion

In order to determine the tangential moisture diffusion coefficient for wood, the following approximate relationship is used (Luikov 1966):

$$a_m = 0.845 \times 10^{-18.3} \times T^{10} \times \rho_0^{-3.9} \left[\frac{m^2}{h}\right] \qquad \text{Equation 16}$$

where T is the average wood temperature, considered to be initially equal to the wet bulb temperature. The ovendry wood density is $\rho_0 = 430\, kg/m^3$.

In Figure 1 the hygrometric criterion - time variation, in 3 locations on the board thickness, based on Equation 9 and the standard drying schedule, is shown. It is obvious that the criterion is quite not sensitive to the *x* coordinate. The figure shows also the increase of the hygrometric criterion with time.

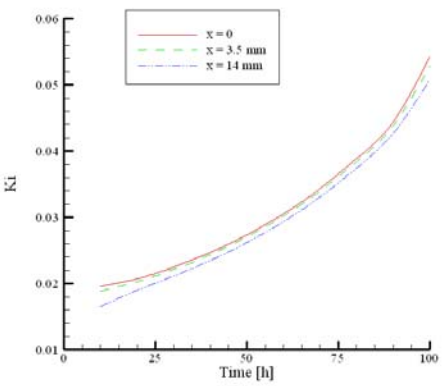

Figure 1: Hygrometric criterion variation in time at different thicknesses for the standard drying schedule

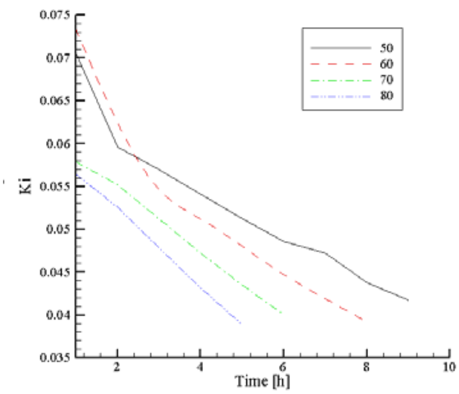

Figure 2: Hygrometric criterion variation in time for RH=40% and different dry-bulb temperatures

In Figures 2, 3 and 4 there are shown the graphical representations of the hygrometric criterion - time variation with respect to the considered drying schedules. It is to observe the increase of the hygrometric criterion once the relative humidity decreases. It is also interesting to note the decrease of the criterion with temperature increase. Therefore, high temperature and relative humidity values reduce the risk of checking. For all three drying schedules, the hygrometric criterion decreases with time.

The increase or decrease of the hygrometric criterion, if comparing Figure 1 with Figures 2, 3 and 4, can be explained by comparing Equations 9 and 15. Therefore, according to Eq. 9 the following relation must hold $\frac{\overline{M}_0 - M(x,\tau)}{\overline{M}_0 - EMC} > Fo^* - \frac{R^2 - 3x^2}{6R^2}$ and according to Eq. 15, $\frac{\overline{M}_0 - \overline{M}(\tau)}{(\overline{M}_0 - EMC)} < Fo^*$.

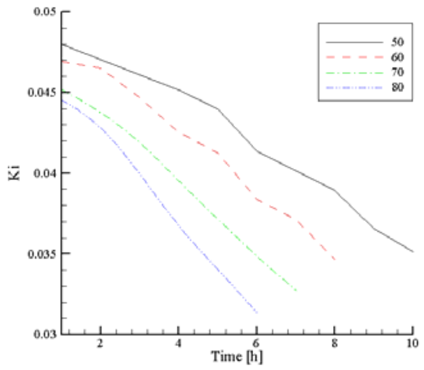

Figure 3: Hygrometric criterion variation in time for RH=50% and different temperatures

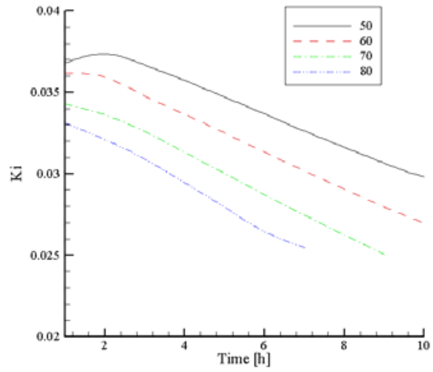

Figure 4: Hygrometric criterion variation in time for RH=60% and different temperatures

The mathematical drying quality assessment was performed for the first drying period, for which, according to the TORKSIM wood drying simulation programme, no relative stresses occur. For this reason, in order to obtain the critical Kirpichev number, it was necessary to consider the supplementary moisture content interval 30-20%, from where that time moment was taken when the first relative stress has been recorded. The average board temperature and moisture content were considered also at the same time moment. Fig. 5 shows that the minimum criterial values are placed between 70^{o}C and 80 ^{o}C. Again, the minimum checking risk occurs at 80 ^{o}C and 60% RH.

According to Fig. 6, the checking risk decreases with the average moisture content decrease. The most checking risks are encountered in the moisture content interval 23-25%. The checking assessment is approximate because the mathematical model was developed for the first drying period.

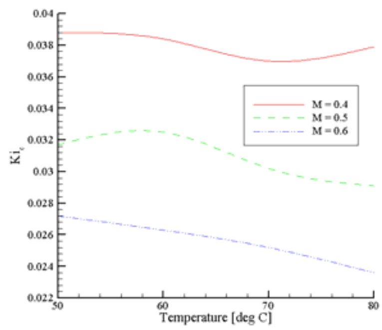

Figure 5: Critical hygrometric criterion as a temperature function for different RH

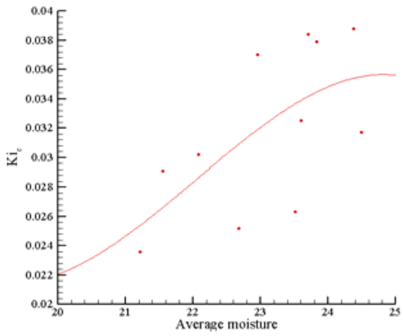

Figure 6: Critical hygrometric criterion as an average moisture content function

The correlation between the criterion and the relative stress is represented in Figure 7. It can be observed that there is a good correlation between the two criteria, the correlation factor being $\frac{Ki_c}{RS} \cong 0.1$, where *RS* refers to the relative stress.

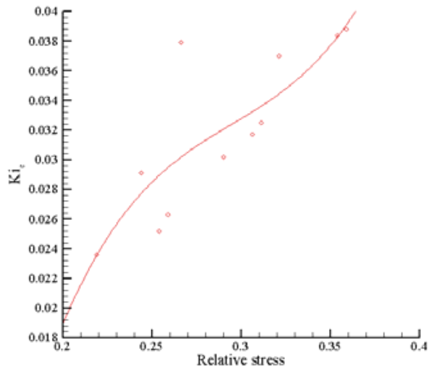

Figure 7: Critical hygrometric criterion – relative stress correlation

5 Conclusions

In this paper a hygrometric criterion of similarity is determined, which can be used to describe the moisture content profile when there is a probability for the surface cracks occurrence. The constant-rate drying period was considered, when the mass transfer intensity is maximum. The system of partial differential equations governing the phenomenon consists of the unsteady energy and mass (moisture) equations and it was considered in its 1D version. The analytical solution given by Luikov and the numerical simulation performed with TORKSIM (version 5.0) were combined in order to derive the appropriate hygrometric criterion.

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References

Almeida, G., Pontin, M., Hernández, R.E. (2005) "Changes in shrinkage of temperate and tropical hardwoods below and above the fiber saturation point", 9th International IUFRO Wood Drying Conference, Nanjing, pp. 453-458.

Keey, R.B. (1994) "Heat and mass transfer in kiln drying: a review", 4th International IUFRO Wood Drying Conference, Rotorua, pp 22-44.

Luikov, A.V. &Mikhailov, Yu.A. (1965) "Theory of energy and mass transfer", Pergamon Press.

Luikov, A.V. (1966) "Heat and mass transfer in capillary-porous bodies", Pergamon Press.

Scheepers, G., Danvind, J., Morén, T. Rypstra T. (2005) "An investigation of fluid water movement in birch during drying through variation of wood sap surface tension and initial average moisture content", 9th International IUFRO Wood Drying Conference, Nanjing, pp. 57-62.

Song, J.H.& Shida, S. (2010) "Infrared thermography for monitoring surface checking of wood during drying", 11th International IUFRO Wood Drying Conference, Skelleftea, pp 70-75.

Seba Industrial "User manual".

TORKSIM ver. 5.0 "User manual and instructions for evaluation of calculated results", SP Wood Technology, SP Technical Research Institute of Sweden.