Determination of Effective Diffusion Coefficient and Mechanical Stress of Pine Wood during Convective Drying

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Abstract

The aim of this study was to find significant correlations between these three components: industrial experiments of drying, drying simulation program and laboratory experiments of drying. The study concentrates on the examination of the dependence of effective diffusion coefficient on mean moisture content in the process of convective drying of pine (*Pinus sylvestris* L.) sawn timber. The methodology of experimental determination of effective diffusion coefficient and the laboratory equipment is described and the results of the experiment are compared to the results received by means of one dimensional simulation programme TORKSIM ver. 3.1. For experimental determination of effective diffusion coefficient necessary measurements of the moisture content of wood were made using the method based on electrical conductance/resistance. In the course of drying processes 12 effective diffusion coefficients dependent on the moisture content of pinewood were determined on a trial basis.

Laboratory experiments were carried out to register the time of initiation of the first crack on the surface of the pinewood from the start of the drying process, and the results were compared to the maximum relative tensile stress on the surface of the pinewood simulated by the computer programme TORKSIM ver. 3.1. On the basis of the results of the simulation, the maximum relative compressive stress was determined in the core of the pinewood board subjected to drying.

One-dimensional (1D) moisture profile from the surface to the core of the board was measured and the results were compared to the simulated moisture profile of the programme TORKSIM ver. 3.1. Comparison of the moisture contents measured in the laboratory experiment and simulated by the programme showed that best matching of the moisture contents was achieved in the near-surface layer of the board sample. It was concluded that the laboratory equipment was suitable for the assessment of the accuracy of the wood drying simulation programme TORKSIM ver. 3.1 as well as for repeating the drying schedules used in industrial wood drying.

Key words: heat transport, moisture transport, effective diffusion coefficient, tensile stress, compressive stress

Introduction

The indicators of convective drying of wood (i.e. final moisture content, mechanical stresses, initiation of cracks in the wood etc.) are determined by the choice of the drying schedule. Nowadays drying control programmes for kilns are developed by mathematical modelling, i.e. computer simulation (Salin 1990, Rémond et al. 2007) of the drying process. Simulated drying schedules are carefully tested both under laboratory conditions and in industrial environment (Tronstad et al. 2005).

It can also be done conversely by taking a drying schedule which has proved to function efficiently in industrial kilns and test it under laboratory conditions. At the same time computer simulation for the drying process is performed. Certain difficulties can be encountered with the evaluation and interpretation of the results of using commercial simulation programmes, as the exact mathematical model which is the basis for the commercial programme is not known to the user. In most cases general information about the simulation programme is known – i.e. whether the model is one-, two- or three- dimensional (1D, 2D, 3D Model), isotropic or orthotropic. Sometimes background information can be obtained from other sources like a description of the mathematical model likely used in the simulation programme (Salin 1990, Rémond et al. 2007).

Direct experimental determination of the diffusion coefficient according to Fick's First Law is a widely used method. The main reason being that the method enables the local diffusion coefficient to be determined in different locations of the wood sample subjected to drying, dependence of the diffusion coefficient on moisture, temperature and coordinate, i.e. the function *D (u,T,x)* can be examined by means of experiments. The diffusion coefficient can be determined by oven-dry method (Hukka 1999, Tremblay et al. 2000), computed tomography, x-ray scanning (Danvind 2005, Cai 2008) and electrical conductivity method (described in this paper). However, only the oven-dry method can be considered as an absolute method, i.e. a method which does not require any comparison or calibration with other methods.

The aim of the study has grown out of practical needs, not laboratory research. The aim was to find significant correlations between these three components: industrial experiments of drying, drying simulation program and laboratory experiments of drying.

Materials and methods

The coupled, uncoupled and diffusion-based simplified models

The coupled model to calculate the combined heat and moisture transport through a porous medium was developed by Luikov (1966), and specific to wood by Siau (1984).

The governing equation for heat transfer through wood board is as follow:

$$\rho c_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(\lambda \frac{\partial T}{\partial x}\right) + \frac{\partial u}{\partial t} \rho_w G_m H_m , \tag{1}$$

where x is the distance along the direction flow (m); t is the time (s); ρ is the wood density (kg m^{-3}), as a function of moisture content u; c_p is the specific heat capacity of wood (J kg^{-1} K^{-1}), as a function of temperature and moisture content u (kg kg^{-1}); T is temperature (K); λ is wood thermal conductivity (W m^{-1} K^{-1}), expressed as a function of temperature and moisture content u; ρ_w is the water density (kg m^{-3}); G_m is the wood specific gravity (kg kg^{-1}) and H_m is the latent heat of moisture in wood (J kg^{-1}). The specific gravity of wood, G_m is the ratio of the density (mass of a unit volume i.e. oven-dry mass of wood) of a substance to the density (mass of the same unit volume i.e. mass of water) of a reference substance. The moisture content u in the wood material is expressed as the weight of water present in the wood divided by the weight of oven-dry wood substance.

The governing equation for unsteady state isothermal moisture transfer through a wood board is given as the Fick's Second Law (Crank 1956) in one dimension:

$$\frac{\partial u}{\partial t} = \frac{\partial}{\partial x}(D_t(T,u)\frac{\partial u}{\partial x}) , \tag{2}$$

where D_t is the transverse wood moisture diffusion coefficient (m^2 s^{-1}).

It is possible to simplify a coupled model and turn it into an uncoupled model on the assumption that there is no heat generation inside the wood. This assumption can be roughly implemented if the experiment fulfills certain conditions – i.e. in the case that the velocity of heat transfer process through the wood sample is over ten times higher than the velocity of mass transfer i.e. diffusion process. Another simplifying assumption would be the use of empirical formula for thermo-physical properties of wood and other non-linear transfer coefficients (Younsi et al. 2006).

In exceptional cases, the isothermal diffusion equation (i.e. Fick's Second Law) can be used to describe the process of drying wood in narrow temperature range 50-60°C with reasonable accuracy (ref. eq. 2). The prerequisite for using the extremely simplified diffusion-based model is presence of as many reference points of comparison as possible which allow us to observe the dynamics of moisture content and temperature. Such drying schedule resulting in parabolic moisture content distribution in the cross-section of the material perpendicularly to the surface was named quasi steady-state by Luikov (1966). In such case Fick's Second Law, eq. (2), can be presented in the following form:

$$D_t \frac{\partial^2 u}{\partial x^2} = const , \tag{2a}$$

The solution of its differential equation is square root function.

Upon experimental determination of the diffusion coefficient it is very important to fulfil the assumptions of isothermal diffusion. Isothermal properties were checked by constant observation of differences in temperature on the surface of the sample and at different distances from the surface of the sample both inside the sample (Figure 1) and in the drying air.

The mathematical model being the basis for the wood drying simulation programme TORKSIM ver. 3.1 has not been disclosed in detail. However, on the basis of Salin (1990) it can be assumed that it is perfect isotropic Luikov-type coupled model.

Stress calculation model

In order to ensure quality in the process of wood drying it is necessary to calculate the strain and stress evolved in wood on the basis of previously calculated moisture profile. The mathematical model in the one-dimensional isotropic case can be presented on the basis of Salin (1990). The primal equation for stress calculation:

$$\sigma = aE\left(\frac{\int_0^{l/2} E\rho_b dx}{\int_0^{l/2} E dx} - \rho_b\right), \quad (3)$$

where σ – tensile stress (Pa); ρ_b –bound water content (kg m^{-3}); E – modulus of elasticity (Pa); l – board thickness (m); x – coordinate from the surface of the board (m).

The governing equation for creep calculation:

$$\frac{\partial \varepsilon}{\partial t} = \frac{1}{E}\frac{\partial \sigma}{\partial t} + \frac{\partial \varepsilon_v}{\partial t} + (a + m\sigma)\frac{\partial \rho_b}{\partial t}, \quad (4)$$

where ε – total strain; σ - tensile stress (Pa); E – modulus of elasticity (Pa); ε_v – viscoelastic strain; a – unrestrained shrinkage coefficient (m^3 kg^{-1}); m – mechano-sorptive creep coefficient (m^3 kg^{-1} Pa); ρ_b – bound water content (kg m^3); t – time (s).

Modulus of elasticity E is not a constant, but depends on both moisture content and temperature.

Material

In this paper the data of computer simulations of two industrial experiments and one laboratory experiment of convective drying of pinewood using the 1D programme TORKSIM ver. 3.1 (Trätek 2006) are presented. Also, the approximate inverse determination of efficient diffusion coefficients is presented using the parabola method well-known from simulated moisture profiles (Kretchetov 1972). The diffusion coefficient in this context is defined as the effective diffusion coefficient of the total diffusion flux of the liquid phase and vapour phase and water and bounded water.

In an industrial kiln samples of pinewood (the length the samples 6 m, dimensions of the cross-section 150x22 mm and 150x50 mm and the sawing pattern 4EX-log), located in the middle of the pile, were dried. The samples of pinewood for the laboratory drying experiment had the cross-section of 200x56 mm and the length of 600 mm. In all three experiments the average content of heartwood was 40% ±10%. In the laboratory experiment the ends and sides of the wood sample were covered with neutral silicone (a product of Bostik) to ensure the validity of the assumptions of the one-dimensional mathematical model in the experiment.

Experiment

In the laboratory drying test the diffusion coefficients were determined experimentally by means of electrical conductivity method Flick's First Law (Fick 1855) was used . In addition, differences in the temperature of the material subjected to drying and initiation of the first drying crack as a result of drying stress were examined. For this purpose, a forced drying schedule three times shorter than the regular schedule commonly used in industry was applied.

In the industrial chamber type convective dryer a reliable mild drying schedule was used to ensure the high final quality of wood. This method has also been successfully tested in practice before. The drying time of the 22 mm sample was 90 hours and for the 50 mm sample the corresponding time was 336 hours. The initial moisture contents were 55 ±10% and 36 ±10%, respectively. The drying chamber was controlled by the relative air humidity and temperature sensor ROTRONIC Hygro Clip-S (measuring range 0 – 100% RH, precision at 23 ºC ±1.5% RH). The wood moisture content was measured by means of screw electrodes in six different points in the location of 1/3 of the thickness of the board from the surface (Figure 1). The values of moisture content were averaged and registered in the log file. Information of the average moisture content of wood was not used in the control of the drying chamber and it was saved as additional information. The average velocity of air in the drying chamber was 2 ms^{-1}. Hysteresis of automatic control in the "on-off" control of the drying chamber was adjusted to ±1.5ºC in the temperature channel and to ±2% RH in the relative humidity channel of drying air. During the drying process a schedule with linearly rising temperature on average of 0.01ºC and 0.1ºC per hour was respectively used for the samples of the thickness of 22mm and 50mm. In both cases the speed of temperature rise was smaller than the fluctuation of temperature per hour caused by the automatic control system of the chamber (i.e. ±1.5ºC). The drying schedules for 22 mm and 50 mm material are presented in Tables 1, 2 and 3.

The laboratory experiment with pinewood was carried out in the climate chamber FEUTRON. The forced drying schedule is presented in Tables 1 and 4. The climate chamber was operated according to relative air humidity and temperature of the same type of sensor (ROTRONIC Hygro Clip-S) as in the industrial experiment. The climate chamber was controlled

Table 1. Parameters of 22 mm pine drying schedule , 91h (industrial test), and 50 mm pine drying schedule, 336 h (industrial test), and 56 mm pine drying schedule, 121 h (laboratory experiment)

Parameters	22 mm, 91 h, industrial	50 mm, 336 h , industrial	56 mm, 120 h, laboratory
Initial MC, %	53	35	60
Dry density, kg/m^3	430	430	430
Air velocity, m/s	2	2	2
Heartwood content, %	40	40	40

Table 2. Schedule of 22 mm pine drying (91 h industrial test)

Drying time (h)	Dry bulb temp (°C)	Wet bulb temp (°C)	Relative humidity (RH %)
0	5.4	5.4	99.5
10	50.0	49.9	99.5
19	50.0	50.0	94.5
43	60.0	55.9	81.0
67	60.0	50.2	59.0
79	60.0	44.3	41.0
88	60.0	45.3	43.7
91	51.0	38.2	45.0

Table 3. Schedule of 50 mm pine drying (336 h industrial test)

Drying time (h)	Dry bulb temp (°C)	Wet bulb temp (°C)	Relative humidity (RH %)
0	8.1	6.9	84.6
15	50.0	48.7	92.7
72	50.0	48.1	89.6
192	55.4	51.3	80.1
300	55.4	43.5	50.0
336	30.0	22.7	53.6

Table 4. Schedule of 56 mm pine drying (121 h laboratory experiment)

Drying time (h)	Dry bulb temp (°C)	Wet bulb temp (°C)	Relative humidity (RH %)
0	20.0	10.9	30
1	50.0	48.5	92
121	60.0	44.0	40

by “on-off” system in which the hysteresis of automatic control was adjusted to ±1.5°C in the temperature channel and to ±2% RH in the relative humidity of air channel – the same as in the case of the industrial experiments. The temperature rise in the laboratory experiment was linear, 0.08°C per hour. In the laboratory experiment the temperature range was 50°C - 60°C, i.e. the same as in the industrial experiment. The difference between the laboratory experiment and the analogous industrial experiment (50 mm pinewood) was the duration of the experiment – the laboratory experiment was carried out in a time period of about 1/3 of that of the industrial experiment (120 hours and 336 hours, respectively).

Location of different sensors in the single specimen, on the surface and near the surface of the sample in the laboratory experiment is shown in Figure 1.

Differences of temperatures in the sample, on its surface and in the ambient air were registered by a thermocouple of AHLBORN (type FTA 3901, resolution of 0.1K) and the data were saved using a nine-channel data logger AHLBORN ALMEMO 2890-9. The locations of five thermocouples were 10 mm from the surface of the sample in the air, on the surface of the sample and in the depth of 4.5 mm, 9 mm and 28 mm in the sample. The moisture content of wood was measured from the same depths using AHLBORN timber moisture sensors (type FHA 636M) and the data was saved by the data logger. Also, the moisture content of wood was measured manually at least twice in 24 hours using moisture measuring device GANN HYDROMETTE HT 85T from the depths of 4.5 mm and 9 mm from sapwood (board thickness 56 mm) and 28 mm from heartwood. The velocity of air was registered by AHLBORN thermo-anemometer of type FVA645 TH2 at 10 mm from the surface of the sample. Strain in the surface layer of the sample and the time of initiation of the first drying crack were registered by the data logger and a displacement sensor of type FWA 025T with the resolution of 0.001 mm.

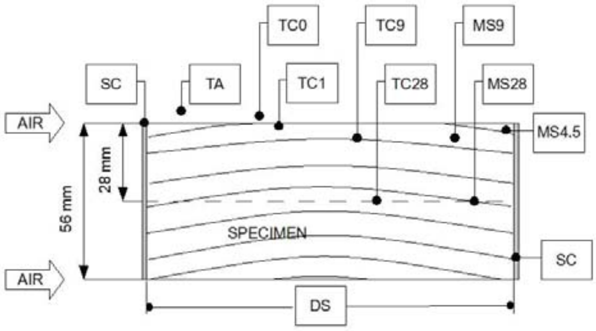

Figure 1. Location of sensors in the sample
(TC – thermocouples TC0 in air, TC1 under the surface, TC9 9 mm from the surface; TC28 28 mm from the surface; MS – moisture content sensors 4,5 mm, 9 mm and 28 mm distance from surface; DS – displacement sensor; TA – thermo-anemometer; SC - silicon coating)

The accuracy of AHLBORN (type FHA 636MF) timber moisture sensors used in the experiment was ±2% (the accuracy depends on MC). The accuracy data is not presented in the manual of GANN HYDROMETTE HT85T, which was used for manual measurement of moisture content of the wood. However, the instrument is operating on the principle of electric resistance of wood and thus, the accuracy could be considered to be the same as that of Ahlborn sensors (i.e. ±2%). In the experiment the moisture flux and gradient were measured with the same sensor. As the diffusion coefficient was calculated as the quotient of these two indications the accuracy of the determination of the diffusion coefficient is ca ±4%. According to Gann (2011) the accuracy of conductance type moisture sensors decreases above fibre saturation point (FSP) compared to the accuracy below FSP.

Multiple regression analysis was done in the statistical software environment of R (2011).

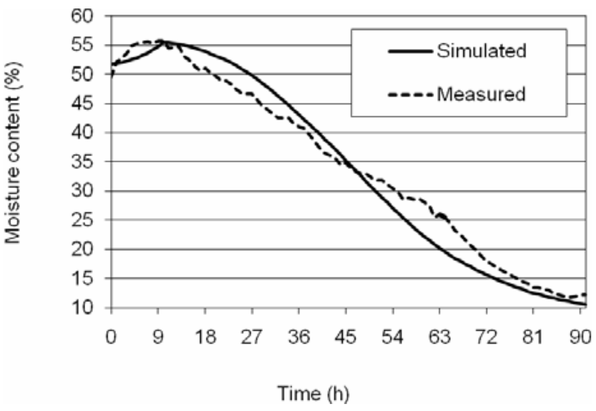

Figure 2. The graphs of log file and simulation of the results of industrial drying experiment (pine board thickness 22 mm, measurements based on electrical conductance, simulated with TORKSIM ver. 3.1)

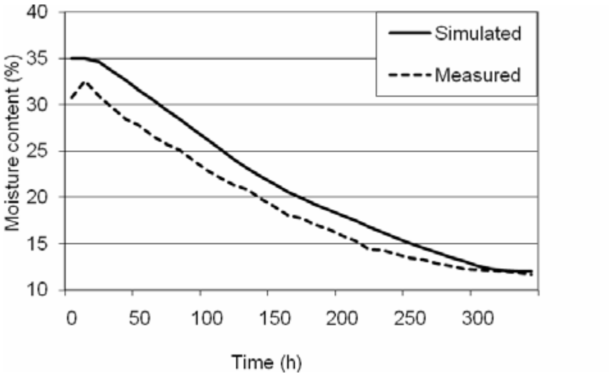

Figure 3. Results of mean moisture content simulations with the programme TORKSIM ver. 3.1 compared with industrial measurement (pine board thickness 50 mm)

Results

The graphs of log files of the results of industrial drying experiments and relevant simulations with the programme TORKSIM ver. 3.1 are shown in Figures 2 and 3.

For 22 mm material (Figure 2) the formula of linear regression was:

MC(m) = 4.43437 + 0.88278 MC(s),

Multiple R-squared: R^2=0.9775, where

MC(m) – measured mean moisture content MC and

MC(s) – simulated mean moisture content MC.

Comparison of the MC(m) and MC(s) gave the standard deviation 2.94%.

For 50 mm material (Figure 3) the formula of linear regression was:

MC(m) = 0.886608 +0.853483MC(s),

Multiple R- Squared: R^2 =0.9919,

Comparison of the MC(m) and MC(s) gave the standard deviation 2.60%.

Maximum differences in the temperature on the surface of the sample and inside the sample did not exceed ±0.7°C (Figure 4). Also TORKSIM ver. 3.1 shows differences in the temperature on the surface of the sample and in the drying air near the surface of the sample. There was a good match with the differences in temperature measured in the course of the experiment (Figure 4).

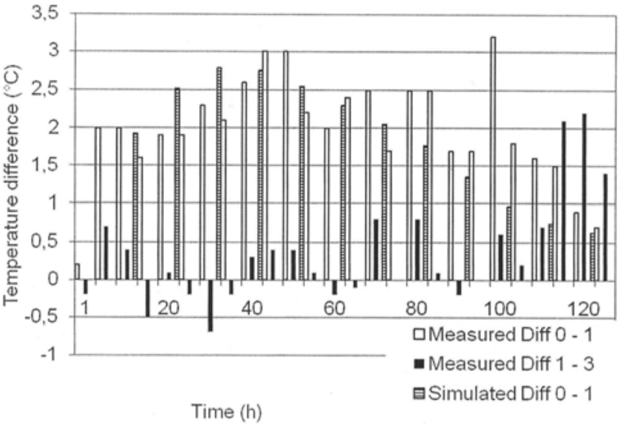

Figure 4. Results of the measurements of temperatures and the simulation (laboratory experiment and simulation)
Diff 0 - 1 measured temperature difference between air and surface of board
Simulated Diff 0 - 1 simulated temperature difference between air and surface of the board
Diff 1 - 3 measured temperature difference between surface and core of board

Processing of the simulation results of industrial experiments with programme TORKSIM ver. 3.1 (22 mm pine 91 hours and 50 mm pine 336 hours) showed strong correlation with the quasi-stationary drying regime, the values of R^2 varied within the range of R^2= 0.991 – 0.9999, 22 mm board and R^2=0.9939 – 0.9998, 50 mm board, respectively (example in Figure 5).

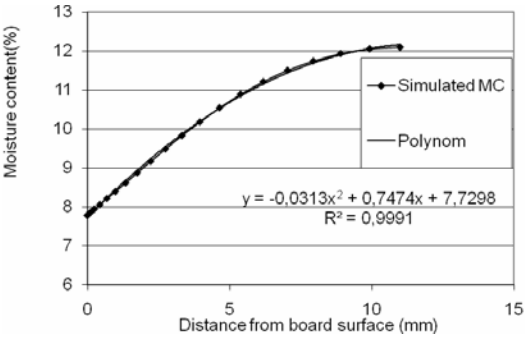

Figure 5. Example of approximation of the simulation of distribution of moisture content with the second level polynomial or parabola equation

Correlation with the quasi-stationary drying regime was weaker in case of forced drying regime in the laboratory experiment when drying a 56 mm pine board for 121 hours. Processing of the simulation results demonstrated variation of R^2 in the range of R^2= 0.9821 – 0.9885. Measured and simulated local MC in the depths of 4.5 mm, 9 mm and 28 m from the surface of the board were compared in the laboratory experiment using the forced drying regime (drying 56 mm pine board for 121 hours) and the results are shown in Figure 6.

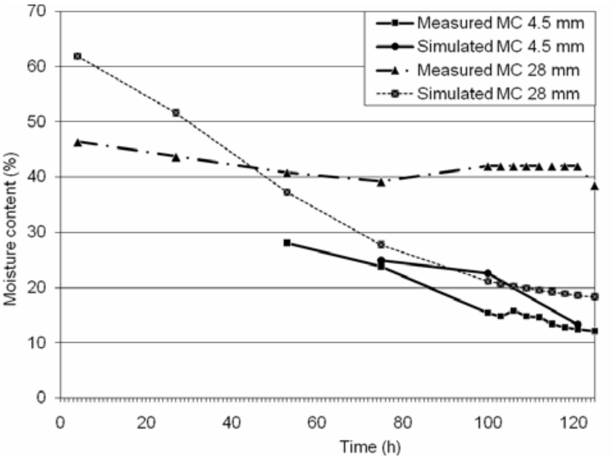

Figure 6. Comparison of the moisture content measuring data of the laboratory experiment with computer simulation (depth levels 4.5 mm and 28 mm)

According to the simulation results the moisture content can also be determined by the first time derivate. These data enabled the approximate inverse determination of diffusion coefficient by means of the parabola method (Kretchetov 1972) well-known from the Fick's Second Law. Also, it was possible to define the dependence of inversely determined diffusion coefficients on the mean moisture content of wood shown on Figures 7 and 8.

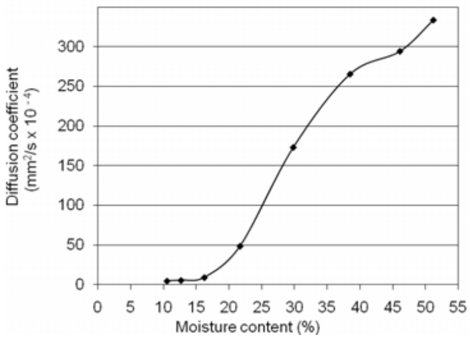

Figure 7. Dependence of inversely determined diffusion coefficients on mean moisture content of wood (pine board thickness 22 mm)

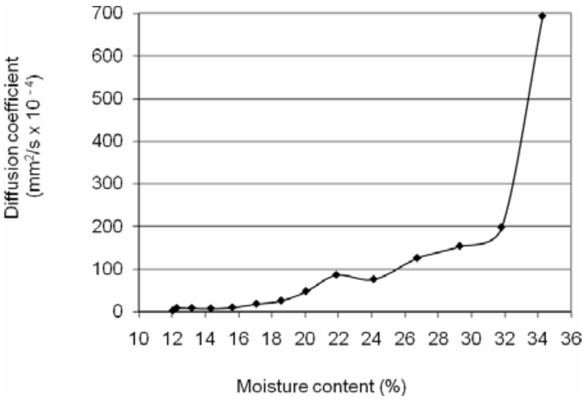

Figure 8. Dependence of inversely determined diffusion coefficients on mean moisture content of wood (pine board thickness 50 mm)

Figure 9 shows the dependence of the diffusion coefficient on approximate inverse determination of TORKSIM simulation and on the local diffusion coefficient determined directly by the laboratory experiment from the mean wood moisture content (MC).

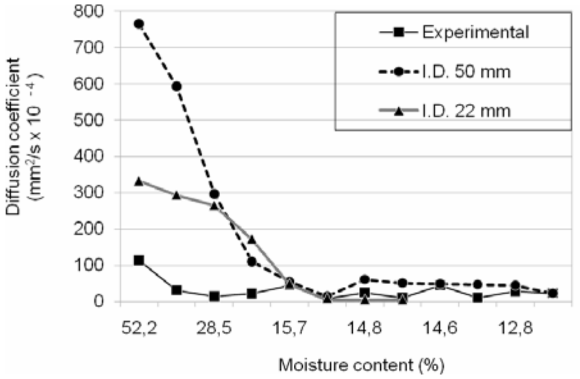

Figure 9. The dependence of the diffusion coefficient of inverse determination (I.D.) of TORKSIM simulation (I.D. 50 mm and I.D. 22 mm) and the diffusion coefficient determined directly by the laboratory experiment from the mean moisture content (MC)

The first crack in the 56 mm thick pinewood sample emerged 82 hours after the initiation of the drying. The computer simulation of the laboratory experiment indicated maximum relative tensile stresses of the value of 0.33 units at 80 - 90 hours referring to the risk of initiation of drying cracks. Distributions of tensile and compressive stress at a defined moment of time (75, 82 and 121 hours from the start of the drying process) were found in a simulation in the laboratory experiment. The result is shown in Figure 10.

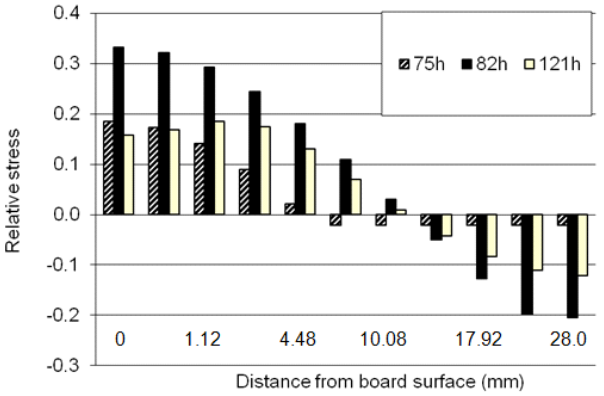

Figure 10. Distributions of relative tensile (marked with plus) and compressive stress (marked with minus) at a defined moment in time 75, 82 and 121 hours from the start of the drying process, were determined in a simulation in the laboratory experiment

Discussions and conclusions

The accuracy of experimental determination of the diffusion coefficient in a given coordinate point was largely dependent on the resolution capacity and time stability of the measuring device. As the gradient itself is a function of the coordinate, the accuracy was also dependent on the size of the measured sample. When comparing the accuracy of experimental determination of the diffusion coefficient with the method of computed tomography ±3.6% (Danwind 2005) and conductivity method (±4%) it appeared that the difference in accuracy was not significant. The achieved accuracy can be considered satisfactory for diffusion-based control of wood drying. The problem with the tests was that the moisture content above FSP was not verified by the reliable oven-dry method. When comparing the measuring data of the laboratory drying experiment with computer simulation, relatively good match between the measured and simulated moisture content in the layer near the surface of the sample was observed. However, the moisture content in the middle part of the sample measured at the end of the experiment was considerably higher (39 ±10%) than in case of simulation (18%). Probably the moisture content in the middle of the sample was measured with lower accuracy, as the accuracy of conductance type moisture sensors decreases above FSP.

During the study the approximate inverse determination of effective diffusion coefficient by the parabola method was applied. To use this approximate method for analysis, the code of the commercial simulation programme TORKSIM ver. 3.1 was not essentially needed. The results of the study showed that the electric devices for measuring moisture content can be used for experimental determination of the diffusion coefficient according to Fick’s First Law.

The results of the study indicate that there is good correlation between the moisture content of wood measured during the industrial experiment and the results of computer simulation. It was proved that by the method of electrical conductivity the effective diffusion coefficient dependent on the mean moisture content can be used as an alternative to the oven-dry method. The effective diffusion coefficients can be the basis for comparison of (industrial or laboratory) experiments and corresponding computer simulations. These outcomes are important for improving the method in the future.

During the laboratory experiment, forced drying schedule was used to test the limits of the simulation model by co-ordinate. It was found, that the simulation programme precisely predicted the appearance of first cracks during the experiment. The simulation of the industrial experiments proved, that the high quality of drying of wood can be predicted by the computer simulation of the process. This is not surprising as the simulation programme TORKSIM ver. 3. 1 has been tuned according to the results of 28 full-scale industrial experiments of drying of pine wood.

The accuracy of the results of the measurements above FSP could be influenced by compensation of systematic errors during measurement of small differences of moisture contents. Still it should be mentioned, that the range above FSP is not relevant from the point of view of quality of the drying process, as the shrinkage of wood does not take place above FSP. Usually parts of sawn timber reach FSP at different times, surface earlier than inner parts. This phenomenon was not observed as mild drying schedule was used for this experiment.

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ОПРЕДЕЛЕНИЕ ЭФФЕКТИВНОГО КОЭФФИЦИЕНТА ДИФФУЗИИ И МЕХАНИЧЕСКИХ НАПРЯЖЕНИЙ ДРЕВЕСИНЫ СОСНЫ ПРИ КОНВЕКТИВНОЙ СУШКЕ

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Резюме

В данной работе исследуется зависимость эффективного коэффициента диффузии древесины сосны от среднего содержания влажности при конвективной сушке. Описываются метод и лабораторное оборудование для экспериментального определения эффективного коэффициента диффузии. Результаты проведенных экспериментов сопоставлены с результатами, полученными одномерной компьютерной программой для моделирования сушки древесины TORKSIM версии 3.1. Для экспериментального определения эффективного коэффициента диффузии проведен ряд измерений влажности древесины при помощи влагомера, работающего на основе измерения электропроводности.

В процессе сушки древесины сосны, была экспериментально определена зависимость эффективного коэффициента диффузии от среднего содержания влажности. Во время эксперимента было зафиксировано время появления первой трещины на поверхности образцов с начала сушки. Полученное значение времени сопоставлено с компьютерной моделью, где действуют максимальные относительные напряжения растяжения на поверхности древесины. На основе компьютерной модели были определены максимальные относительные напряжения сжатия в средней части исследуемого образца.

Во время сушки измерен также одномерный профиль влажности образцов от поверхности до середины и сравнено с профилем, полученным при помощи компьютерной программы TORKSIM.

Сопоставление результатов, полученных экспериментальным путем и компьютерным моделированием, показало, что значения локального содержания влажности в обоих методах наиболее совпадают на поверхностных слоях древесины сосны.

Эксперименты подтвердили, что использованное в экспериментах лабораторное оборудование подходит как для оценки точности результатов, полученных одномерной компьютерной программой для моделирования сушки древесины TORKSIM, так и для повтора планов сушки сушилок, используемых в промышленности.

Ключевые слова: теплопроводность, влагопроводность, эффективный коэффициент диффузии, напряжение растяжения, напряжение сжатия