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MEASUREMENTS DURING WOOD DRYING BASED ON X-RAY AND SLICING TECHNIQUES AND COMPUTATION OF DIFFUSION COEFFICIENTS

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Abstract

Features of convective drying wood are mainly determined by the character of the internal moisture transfer. The internal resistance depends on wood structure, its temperature, moisture content, moisture flux direction and can be described by the diffusion coefficient. The modified method of the inverse determination of the diffusion coefficients was used in the paper. Measuring the moisture content distributions in the wood during the drying was carried out using slicing and x-ray techniques. After processing the moisture distribution data obtained by the slicing technique the dependence of the diffusion coefficient of birch in the radial direction on moisture content at 65°C was established. With the help of X-ray technique the moisture content profiles in small aspen and pine samples during drying in roomed conditions were obtained. However, the obtained data allowed us to calculate only the average values of the diffusion coefficients in the radial direction. They were equal $1.64 \cdot 10^{-10} m^2/s$ *and* $1.94 \cdot 10^{-10} m^2/s$ *for aspen and pine, respectively.*

Key words: *wood drying; moisture content distribution; slicing technique; x-ray technique; diffusion coefficient; inverse method.*

INTRODUCTION

Timber drying is an important process in the manufacture of wood products. This is a complex process during which heat and mass transfer occurs. Features of convective drying wood are mainly determined by the character of the internal moisture transportation. When the low-temperature drying the moisture in wood moves mainly as a liquid due to the moisture content gradient. The internal resistance depends on wood structure, its temperature, moisture content, moisture flux direction and can be described by the diffusion coefficient.

There are two groups of direct methods of determining the transport properties of wood. The first one so-called cup methods is based on Fick's first law of diffusion and data from the steady-state experiments of bound water transfer (Skaar 1954, Choong 1965, Siau 1984, Lee et al. 1991). Other group of sorption methods is based on the unsteady-state experiments and Fick's second law of diffusion (Comstock 1963, Choong and Fogg 1968, Absetz et al. 1993, Wadso 1993).

Later some methods of the inverse determination of the diffusion coefficients in the one-dimensional non-steady diffusion equation were suggested (Hukka 1999, Liu et al. 2001, Olek and Weres 2001, Weres and Olek 2005, Zhou et al. 2011).

Now the values of diffusion coefficients for many wood species and various conditions can be found in the literature. These data were obtained from the direct or indirect experiments at stationary or non-stationary processes of moisture transfer. In many cases the diffusion coefficients of wood of the one and the same specie, obtained by different researchers differ significantly from each other. Apparently this is due to the variability of wood properties and difference in techniques and accuracy of measurements of the moisture content profiles. In particular, inverse solutions are sensitive to changes in local moisture content in the experimental sample.

The accuracy of mathematical simulation of wood drying and other processes depends significantly on the reliability of the used coefficients. Therefore reliable experimental methods of determining diffusion coefficients of wood are always of practical interest.

OBJECTIVE

The objective of this paper was to determine the diffusion coefficients using classical and non-destructive measurements of moisture content profiles in wood samples with different initial moisture content distributions at convective drying in laboratory drier.

MATERIALS AND METHODS

As experimental data the moisture content profiles over the thickness obtained during the process of drying wood samples were used. For the experiments 6 thin samples made of green birch with specific density of 510kg/m^3 were prepared. Each piece had the dimension 8 x 70 x 800mm^3.

Drying of the samples was carried out at the temperature of 65°C and relative humidity of 60% at air velocity of 2m/sec. The edges and ends of the samples were isolated by applying silicone. To determine the local values of moisture content the slicing technique was used. It is a destructive method where the short cross sections cut from samples were cut with a knife into 8-10 small slices thickness of 0.8-1.0mm. First cross section and slices from it were cut at the beginning of the experiment to determine initial moisture content distribution across the sample thickness. Next sections and slices were cut every 30 minutes during the drying period. After every cutting the fresh sample end was covered by silicone. The moisture content for each cross section and slice was determined with the dry weight method. Balance with the accuracy of weighing 0.001g was used.

The modified method of the inverse determination of the diffusion coefficients in the one-dimensional non-steady diffusion equation were used in the work. Mathematical model of the drying process involves the diffusion equation:

$$\frac{\partial u}{\partial t} = \frac{\partial}{\partial x}\left(a(u)\cdot\frac{\partial u}{\partial x}\right), \tag{1}$$

initial conditions:

$$u(x,0) = u_n(x), \tag{2}$$

and boundary conditions:

$$\frac{\partial u(0,t)}{\partial x} = 0; \quad a(u)\cdot\frac{\partial u(l,t)}{\partial x} = \beta\cdot\left(u_s(T,\varphi) - u(l,t)\right), \tag{3}$$

where: u – moisture content;
x – coordinate;
t – time;
a – diffusion coefficient;
u_n – initial moisture content;
u_s – surface moisture content;
β – mass transfer coefficient;

l – half of sample thickness;
T – air temperature;
φ – air relative humidity.

To determine the diffusion coefficients the objective function *Φ(a)* which is the sum of squared differences between the experimental and theoretical values of the local wood moisture content was used:

$$\Phi(a) = \sum_i \int_0^l \left(u(x,t_i) - u_i^e(x)\right)^2 dx \rightarrow \min \qquad (4)$$

To obtain the moisture content distributions in wood specimens by non-destructive method the X-ray densitometry principle was used in this paper. Measuring the density of experimental samples was carried out on the stand designed on the basis of diffractometer DRON-3 (Fig. 1).

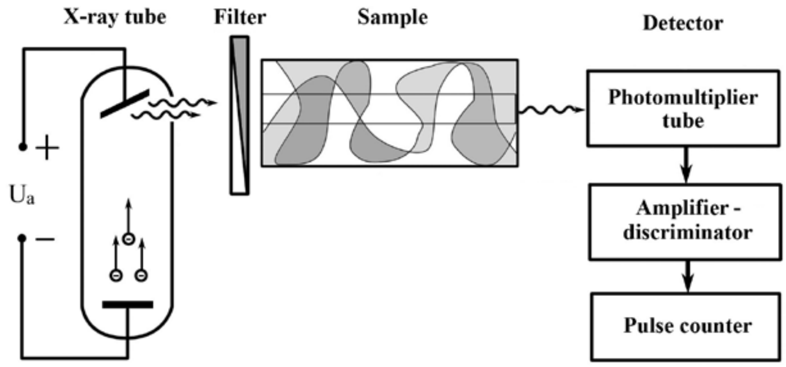

Fig. 1.
Scheme of measuring stand designed on the basis of diffractometer DRON-3

The source of X-radiation of the stand consists of X-ray tube BSV-24Cu with a copper anode and high voltage power supply ESD - 5, providing the voltage up to 50kV and anode current up to 100mA. X-ray detection system consists of a scintillation detector based on the crystal NaJ, photomultiplier tube FAU - 86, amplifier - discriminator and pulse counter. BDS detector unit converts X-ray quanta into electrical impulses, so that quanta of higher energy and shorter wavelength are converted into pulses larger amplitude. This allows to distribute X-ray radiation by wavelength and to carry out spectral analysis of X-ray absorption. Coordinated CoNi - filter selects copper characteristic radiation from the overall spectrum of X-ray tube and together with the discriminator provides a monochromatic radiation with a wavelength of 0,154nm.

The sample was placed between the unit of collimation of the X-ray and detector into coordinate device that provides the horizontal movement perpendicular to the beam. Test specimens were made from aspen wood and pine wood 100mm long, 40mm wide and a thickness of 8 - 12mm. All sides of the samples, except of the evaporation surface, were coated with silicone. Single-sided drying of the samples was carried out at room temperature.

To determine the local wood moisture content the method based on Beer's law was used. Wood containing water is considered as a two-component medium. The following equations allow to describe the absorption of X-rays by water and dry wood:

$$\begin{cases} g_b(x) \cdot \dfrac{\mu_\lambda^b}{\rho_b} + g_w(x) \cdot \dfrac{\mu_\lambda^w}{\rho_w} = \dfrac{1}{\rho(x) \cdot d} \ln\left(\dfrac{I_{0\lambda}}{I_\lambda(x)}\right); \\ g_b(x) + g_w(x) = 1, \end{cases} \qquad (5)$$

where: $g_b(x)$ и $g_w(x)$ – the mass fractions of water and dry wood;
ρ_b и ρ_w – the density of water and dry wood, g/cm^3;
μ_b и μ_w – mass X-ray absorption coefficients for water and dry wood, respectively, cm^2/g;
d – sample length, cm.

Before each experiment, the mass absorption coefficients for water and dry wood were determined. For the wavelength λ = 0,154nm values of these coefficients were equal 9,9sm^2/g and 7,5sm^2/g, respectively. Having the a value of mass fraction of water in every point of the sample it is possible to calculate the local moisture content and to obtain moisture content distribution over the thickness.

RESULTS AND DISCUSSIONS

Fig. 2 shows the moisture content distribution over the thickness of one of birch samples obtained during the drying by means of slicing technique. The initial moisture content distribution was uneven. The right side of the sample was wet than the left. However, after 60 minutes moisture content of the right side decreased faster than the left and the subsequent distributions became approximately symmetrical and similar to cosine curves.

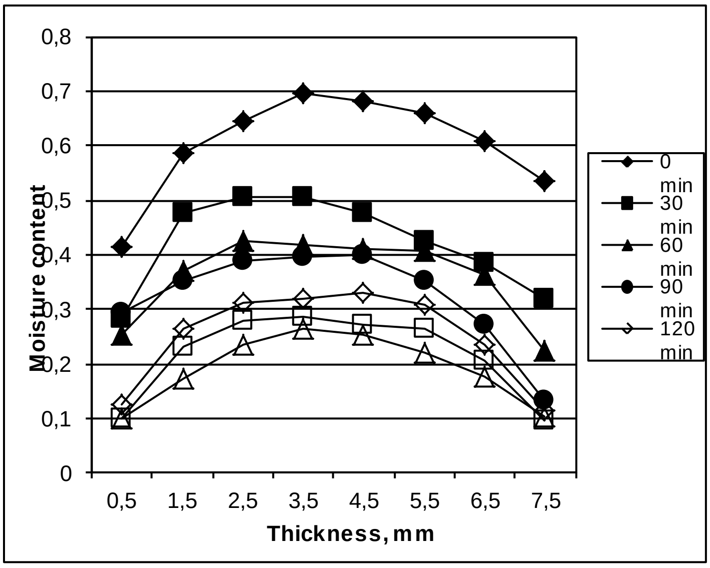

Fig. 2.
Measured moisture content profiles using the slicing technique in birch sample

The dependence of the diffusion coefficient on the moisture content which was calculated over the values of the local moisture content is shown in Fig. 3.

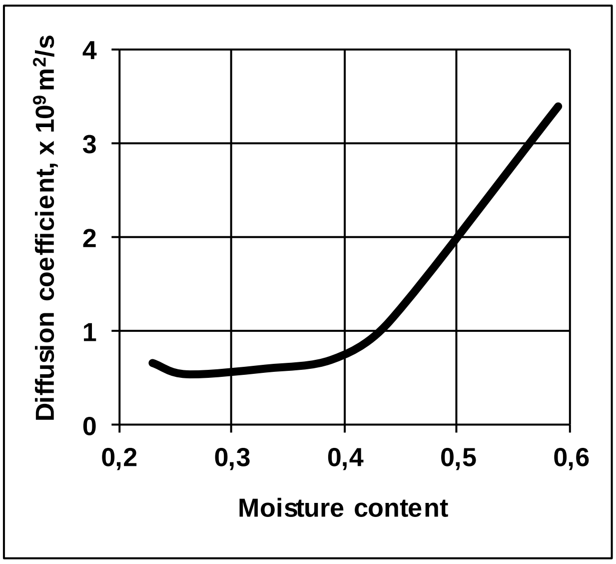

Fig. 3.
Diffusion coefficient versus the moisture content for birch

Increasing humidity leads to non-linear increase of the diffusion coefficient. The growth rate is significantly higher in the range of higher moisture content. A slight decline at the beginning of moisture content range is likely caused by errors in determining the local moisture content.

Moisture content profiles in the aspen and pine samples during drying in room conditions obtained by X-ray technique are presented in Fig. 4 and Fig. 5, respectively.

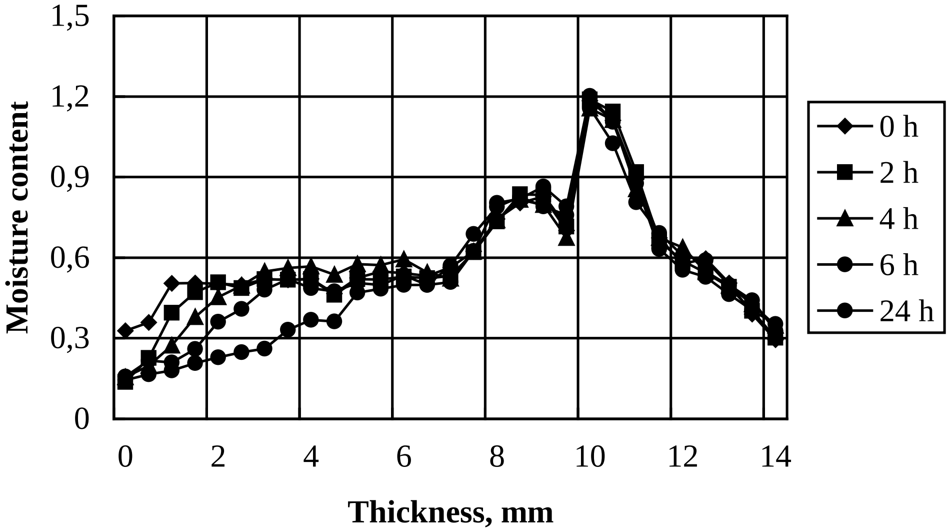

Fig. 4.
Measured moisture content profiles using x-ray technique in aspen sample

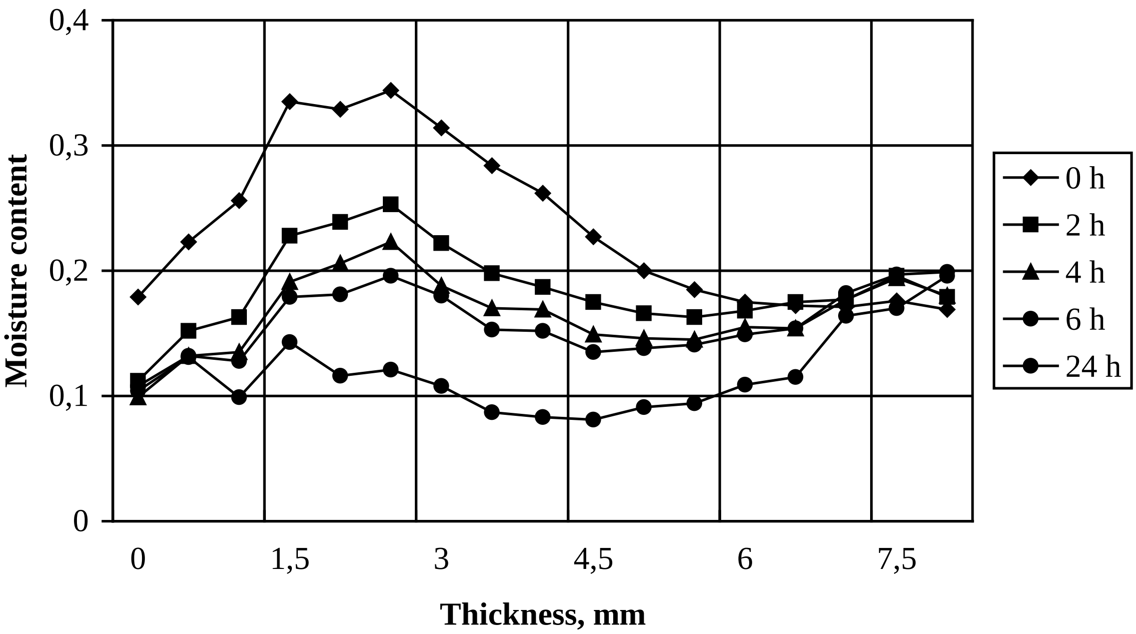

Fig. 5.
Measured moisture content profiles using x-ray technique in pine sample

As seen from the figures, the non-destructive method of measurement of wood moisture content has a much higher resolution compared with slicing technique. X-ray method allows to detect the moisture gradient in small volumes and thin samples. In both experiments, the initial and subsequent moisture profiles had a complex shape with a few bends. Unfortunately, it was impossible to obtain the dependence of the diffusion coefficient on moisture content using these data. Distributions in both samples are very different from cosine curves which are characteristic for the drying processes. Therefore only the average diffusion coefficients in the radial direction were determined. They were equal $1.64 \cdot 10^{-10} m^2/s$ and $1.94 \cdot 10^{-10} m^2/s$ for aspen and pine, respectively.

CONCLUSIONS

The obtained values of the diffusion coefficient are in agreement with data of other researchers. To obtain reliable diffusion coefficients wood samples have to be fairly uniform with a uniform or parabolic initial moisture content distribution.

Slicing technique is relatively simple but time-consuming. It does not require sophisticated and expensive equipment. X-ray technique is perspective method to determine moisture content profiles in wood. Installing the climate station on the stand will allow to study processes of heat and mass transfer in wood and wood based materials under various boundary conditions.

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