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Modelling of Moisture Movement in Wood during Outdoor Storage[*]

R. Baronas[a], F. Ivanauskas[a,b], I. Juodeikienė[c], A. Kajalavičius[c]
[a]Vilnius University, Naugarduko 24, 2600 Vilnius, Lithuania
[b]Institute of Mathematics and Informatics, Akademijos 4, 2600 Vilnius, Lithuania
[c]Kaunas University of Technology, Studentų 50, 3031 Kaunas, Lithuania
[romas.baronas, feliksas.ivanauskas]@maf.vu.lt

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Abstract

A model of moisture movement in wood is presented in this paper in a two-dimensional-in-space formulation. The finite-difference technique has been used in order to obtain the solution of the problem. The model was applied to predict the moisture content in sawn boards from pine during long term storage under outdoor climatic conditions. The satisfactory agreement between the numerical solution and experimental data was obtained.

Keywords: Wood storage, wood drying, modelling, diffusion, pine.

1 Introduction

Trees contain a considerable amount of water. The water or moisture content of wood is expressed as the weight of water present in the wood divided by the weight of dry wood substance. Green (freshly cut) timber may have a moisture content as low as 30% to as high as 250%. To increase the strength and rigidity, as well as to protect the wood against biological damage, most of the moisture must be removed. An energy (heart) must be supplied to evaporate moisture from the wood. The

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drying is a highly energy intensive industrial process, which consumes 7-15% of the total industrial energy in developed countries [1].

The moisture content of wood depends on the relative humidity and temperature of the surrounding air. If wood remains long enough in air where the relative humidity and temperature remain constant, the moisture content will also become constant at a value known as the equilibrium moisture content (EMC).

Lumber dried to 12% or less moisture content, and items manufactured from it, will regain moisture if stored for extended periods under outdoor conditions. Storage of dried lumber is generally not a good practice because of the risk of insect damage. However, storage is sometimes required. Because EMC of wood in outdoor locations is usually high enough to support fungal damage and insect activities, stored lumber should be inspected frequently [2]. The inspection of moisture content in wood is rather complicated and expensive. Another way is to predict moisture content by computer simulation.

Wood in storage is exposed to both long-term (seasonal) and short-term (daily) changes in relative humidity and temperature of the surrounding air. Thus, wood is always undergoing at least slight changes in moisture content [2].

From the mathematical point of view the wood sorption (adsorption/ desorption) problem can be treated as a diffusion problem based on the Fick's second law. A model of the sorption process can be described by the diffusion equation with initial and boundary conditions, which form together the boundary-value problem [3]. Drying models based on the Fick's second law have been successfully used to predict a wood drying process. Several authors have used a wood drying model to solve the inverse problem, e.g., to determine diffusion and surface emission coefficients. Literature survey can be found in [1, 3-5].

In scientific literature moisture movement in wood under isothermal conditions in most cases has been investigated. Isothermal case is much simpler than nonisothermal one. The thermal diffusion should be also taken into consideration when modelling moisture movement in wood under nonisothermal conditions due to the temperature gradient [3, 6]. Since the gradient of temperature in wood is rather low during the outdoor storage, it is reasonable to assume that the temperature distributed uniformly in the specimen and to apply a model of moisture diffusion under isothermal conditions [7].

This paper presents a two-dimensional moisture movement model in which the gradient of temperature is neglected. The model was successfully applied to predict the moisture content in sawn boards from pine during long term storage under outdoor climatic conditions.

2 Moisture Transfer Model

In a two-dimensional formulation, the moisture movement in a symmetric wood piece of thickness $2a$ and width $2b$ can be expressed through the following diffusion equation:

$$\frac{\partial u}{\partial t} = \frac{\partial}{\partial x}\left(D(u)\frac{\partial u}{\partial x} \right) + \frac{\partial}{\partial y}\left(D(u)\frac{\partial u}{\partial y} \right), \qquad 0 < x < a,\ 0 < y < b,\ t > 0, \qquad (1)$$

where x, y are space coordinates, $u = u(x, y, t)$ is the moisture content of wood defined as weight of water in wood expressed as a fraction of the weight of dry wood, t is time, and $D(u)$ is the moisture concentration dependent diffusion function. Though the radial and tangential diffusion coefficient may be different, it was assumed that transverse diffusion coefficient $D(u)$ is the same in the both space directions x and y. The initial condition is that the moisture content of the board is constant:

$$u(x, y, 0) = u_0\ ,\quad 0 \le x \le a,\ 0 \le y \le b\,. \qquad (2)$$

The boundary conditions that describe surface evaporation and symmetry of the specimen are

$$-D(u)\frac{\partial u}{\partial x} + S\,u\bigg|_{x=0} = -D(u)\frac{\partial u}{\partial y} + S\,u\bigg|_{y=0} = S\,u_e\,, \qquad (3)$$

$$\left.\frac{\partial u}{\partial x}\right|_{x=a} = \left.\frac{\partial u}{\partial y}\right|_{y=b} = 0, \quad t > 0, \tag{4}$$

where S is the surface emission coefficient, and u_e is the equilibrium moisture content (EMC) with the ambient air climate. Values of the coefficients D, S and u_e depend on environment (drying) conditions [3]. The coefficients D and S are influenced by species of wood. In addition, the internal moisture transfer coefficient D depends on the moisture content of wood [3, 8, 9].

There are two types of diffusion occurring in wood, intergas diffusion and bound water diffusion [3]. The intergas diffusion is the transfer of water vapour through air in the lumens of cells. The bound water diffusion is water transfer within the cell wall of wood. The transverse diffusion coefficient D can be expressed by the porosity of wood v_a, the transverse bound water diffusion coefficient D_{bt} of wood and the vapour diffusion coefficient D_v in the lumens:

$$D = \frac{\sqrt{v_a} D_{bt} D_v}{(1 - v_a)\left(\sqrt{v_a} D_{bt} + \left(1 - \sqrt{v_a}\right) D_v\right)}. \tag{5}$$

The vapour diffusion coefficient D_v in the lumens can be expressed as:

$$D_v = \frac{M_w D_a p_s}{G_d \rho_w R T_K} \cdot \frac{\mathrm{d}\varphi}{\mathrm{d}u} = \frac{1.29 \cdot 10^{-13} (1.0 + 1.54u) p_s T_K^{1.5}}{(T_K + 245.18)} \cdot \frac{\mathrm{d}\varphi}{\mathrm{d}u}, \tag{6}$$

where M_w = 18 kg/kmol is the molecular weight of water, $D_a = 9.2 \cdot 10^{-9} T_K^{2.5} / (T_K + 245.18)$ is the interdiffusion coefficient of vapour in air [10], G_d = 1.54/(1.0 + 1.54u) is the nominal specific gravity of wood substance at the given bound water content [2], $\rho_w = 10^3$ kg/m^3 is the density of water, R = 8314.3 kmol·K is the gas constant, T_K is the Kelvin temperature ($T_K = T_\mathrm{C} + 273.15$), T_C is the Celsius temperature, φ is the relative humidity (%/100), and p_s is saturated vapour pressure given by [11, 12]:

$$p_s = 3390 \cdot \exp\left(-1.74 + 0.0759 T_C - 0.000424 T_C^2 + 2.44 \cdot 10^{-6} T_C^3\right). \tag{7}$$

The derivative of air relative humidity φ with respect to moisture content u is calculated from the Hailwood-Horrobin equation adopted for wood by Simpson [12] and given as:

$$u = \frac{18}{W}\left(\frac{K_1 K_2 \varphi}{1 + K_1 K_2 \varphi} + \frac{K_2 \varphi}{1 - K_2 \varphi}\right), \tag{8}$$

where

$$\begin{aligned} K_1 &= 4.737 + 0.04773 T_C - 0.00050012 T_C^2, \\ K_2 &= 0.7059 + 0.001695 T_C - 0.000005638 T_C^2, \\ W &= 223.4 + 0.6942 T_C + 0.01853 T_C^2. \end{aligned} \tag{9}$$

The diffusion coefficient D_{bt} of bound water in cell walls is defined according to the Arrhenius equation as $D_{bt} = 7 \cdot 10^{-6} \cdot \exp(-E_b/RT_K)$, where $E_b = (40.195 - 71.179u + 291u^2 - 669.92\,u^3) \cdot 10^6$ is the activation energy [13].

The porosity of wood is expressed as $v_a = 1 - G_m\,(0.667 + u)$, where specific gravity of wood G_m at the given moisture content u is defined as

$$G_m = \frac{\rho}{\rho_w (1 + u)} = \frac{\rho_0}{\rho_w + 0.883 \rho_0 u}, \tag{10}$$

where ρ is density of wood, ρ_0 is density of oven-dry wood (density of wood that has been dried in a ventilated oven at approximately 104°C until there is no additional loss in weight) [2].

Finally, the moisture transverse diffusion coefficient D in wood was expressed as a function of the temperature T_C, moisture content u and oven-dry density ρ_0 of wood. We assumed that the diffusion coefficient remains constant at moisture content above the fiber saturation point (FSP, 30%) [9]. This assumption is not important in case when wood is dried below FSP before storage in outdoor, u_0 less than FSP. Moisture content of wood, that has been dried below FSP, does not usually exceed FSP under outdoor conditions [2].

The surface emission coefficient S in (3) can be expressed as

$$S = \frac{\alpha \varphi_s}{c_p \rho_a \rho_0} \cdot \frac{\mathrm{d}\varphi}{\mathrm{d}u}, \tag{11}$$

where $\alpha \approx 6$ W/m^{2}K is the heat transfer coefficient of air, φ_s is the saturation humidity of air, $c_p \approx 1006$ J/kgK is the specific heat of air, and $\rho_a = 1.292\text{-}0.00428 T_c$ (kg/m^3) is the density of air [5]. The saturation humidity φ_s of air at temperature T_K is expressed as

$$\varphi_s = \frac{p_s}{c_v R_a T_K}, \tag{12}$$

where $c_v \approx 1$ is the compressibility of water vapour, $R_a = 461.51$ Nm/kgK is the ideal gas constant for water vapour.

Equilibrium moisture content (EMC), u_e in (3), is defined as that moisture content at which the wood neither gains nor loses moisture from surrounding atmosphere, an equilibrium condition has been reached. EMC is a function of both relative humidity and temperature of the surrounding air. That function can be expressed as (8) [12].

The average moisture content is measured at various time to predict the dynamics of drying in a physical experiment. The calculated average moisture content $\bar{u}(t)$ values at any time t for a board were determined by numerical integration of the solutions.

Mathematical solutions are not usually possible when analytically solving the differential equations with variable diffusion coefficients and complex boundary conditions, therefore the mathematical model (1)-(4) was solved numerically. The finite-difference technique [14] has been used for the discretization of the model. That technique allows us to solve effectively the differential equations with variable diffusion coefficients and complex boundary conditions. We introduced a non-uniform discrete grid to increase the efficiency of calculations. Since moisture evaporates from the surface of a piece of wet wood, an exponentially increasing (bilinear) step of the grid was used in the space directions from the surface of the specimen to the centre, while a constant step was used in t direction. The explicit difference scheme for equations (1)-(4) has been designed and realised to simulate the moisture movement in the wood specimen [15].

3 Results of Calculations and Discussion

The experimental moisture content values for pine were used for numerical analysis. The samples were cut from central yield boards of the first two pine logs from stump. The sawn boards were cut partially from heartwood and partially from sapwood. The boards were processed into surfaced specimens 50 by 270 by 35 mm. A group of specimens were kept in a meteorological box where the specimens were protected against the direct impact of the sun, rain and wind. The ends of each specimen were insulated (coated) to avoid the moisture exchange from these two surfaces. Specimens were weighted once a week. The experimental moisture content values were the averages of the 6 individual specimens at the same times during the storage. The average oven-dry density ρ_0 of the specimens was 455 kg/m^3. The experimental results have been published [16].

Values of average daily air temperature and relative humidity outdoors were obtained from Kaunas hydrometeorological station. More than one value of temperature and relative humidity was required to simulate numerically the experiment carried out during a day. Because of this an interpolation of the average daily data was required. We used the cubic spline interpolation formula [17] because that is smooth in the first derivative, and continuous in the second derivative, both within an interval and at its boundaries. The cubic spline interpolation was applied for both temperature and relative humidity data.

Since the specimens were relatively long and the ends were heavily coated, usage of the model in a two-dimensional formulation was admissible to predict accurately the process of moisture change. On the other hand, the two-dimensional formulation of the model was required because of relative narrowness of the board used in the experiments [18].

Usually the diffusion coefficient, expressed by (5), applies to wood under isothermal conditions [3]. We employed that expression of the coefficient to the moisture diffusion under outdoor climatic conditions. When calculating it was assumed that the temperature distributed uniformly in the specimen. The same assumption was applied in [7] to predict moisture content in timber-framed constructions under outdoor conditions. This assumption seems to be admissible because the thermal diffusivity is orders of magnitude higher than the moisture diffusivity [2].

Fig. 1 shows the calculated average moisture content values of the specimen as well as experimental data. The moisture movement in wood specimen over all the year 1996 round was simulated. The initial moisture content u_0 equals to 20.5%. Let us notice, that the lowest actual moisture content was in the beginning of September, while the highest in December.

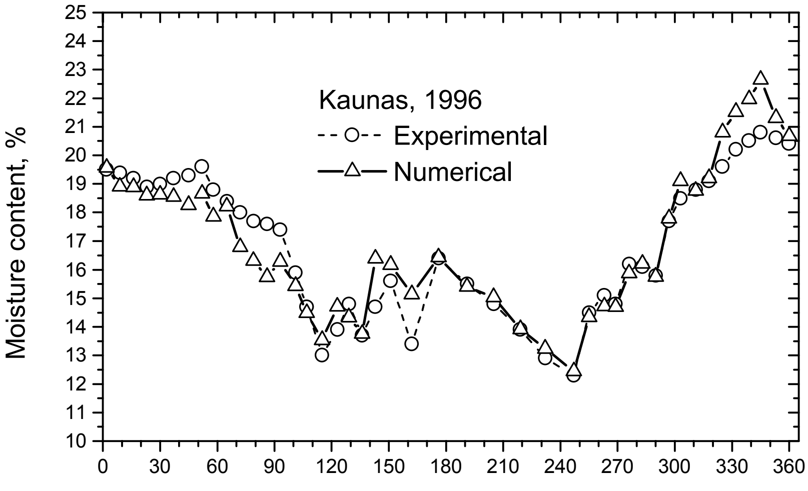

Fig. 1. Experimental data and numerical solutions, Kaunas 1996

The calculated average moisture content values of the specimen as well as experimental data over all the year 1997 are presented in Fig. 2.

The absolute difference between experimental and calculated moisture content values reaches about 2%. This value does not seem very high because of the error of calculation of equilibrium moisture content (EMC) which is about 1.3-2.0% [2, 19]. The error of calculation of EMC may especially be significant at the temperature below $0^{o}C$ [19]. On the other hand, dynamics of moisture content in wood exhibits hysteresis, which means that the EMC is slightly higher if the equilibrium is reached by losing moisture than it would be if it reaches equilibrium by gaining moisture at given relative humidity and temperature. The difference between desorption EMC and adsorption EMC can reach 3% moisture content. The ratio of adsorption EMC to desorption EMC is about 0.85 [2]. Equation (8) defines EMC values for oscillating desorption [12]. This expression is only a reasonable midway between adsorption and desorption. The test samples were initially dried in outdoors. During the experiment, the test samples many times changed the direction of sorption: now adsorption, now desorption. Because of this, the error of calculation of EMC influenced an error of calculation of moisture content of the model specimen.

As it was mentioned the only average daily air temperature and relative humidity were used in simulation of the moisture movement in specimens during storage. Since the function, defining EMC, is highly nonlinear, then the usage of average daily outdoor data also influenced an error of calculations. It would be reasonable to use more detailed data of air temperature and relative humidity.

4 Conclusions

The two-dimensional-in-space moisture movement model (1)-(4) can be successfully applied to predict the moisture content in wood during long term storage under outdoor climatic conditions.

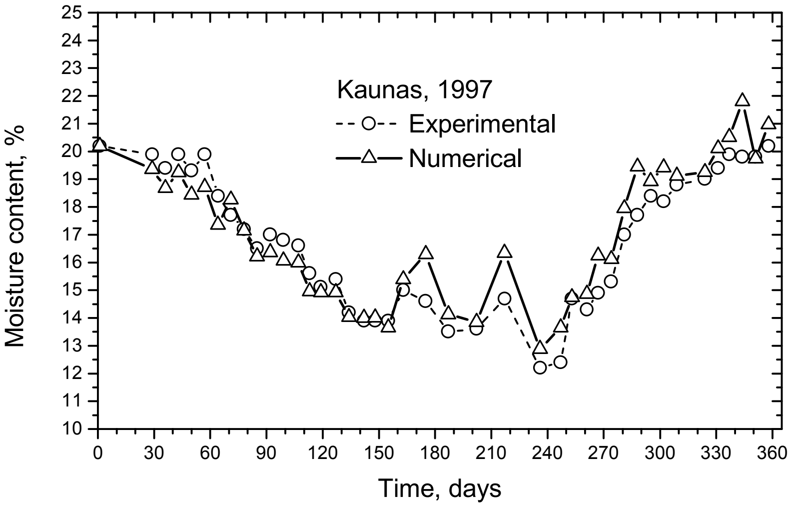

Fig. 2. Experimental data and numerical solutions, Kaunas 1997

The diffusion coefficient, defined by equation (5), which is usually applied to wood under isothermal conditions, may be also applied to moisture diffusion under outdoor conditions.

In modelling of moisture movement in wood during outdoor storage, the temperature in wood may be assumed as distributed uniformly and equals to the temperature of surrounding air.

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